

DECISION MODEL APPLIED
TO GROUNDWATER
REMEDATION

By

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CHAPTER I

INTRODUCTION

This research was aimed at developing a decision analysis model to quantitatively and rigorously evaluate potential remediation approaches at an inactive hazardous and radiological disposal site in northeast Oklahoma. These types of models aid environmental managers, engineers and consultants in selecting the optimal, site-specific remediation technologies to be adopted for cleaning or stabilizing contaminated sites by providing a platform for comparing other alternatives.

Frequently site remediation can prove costly. Many uncertainties exist as to waste locations and concentrations that can significantly increase initial estimates. In 2004, the EPA estimated that in the United States alone, \$250 billion will be required over the next 30 years to clean as many as 350,000 contaminated locations (<http://www.clu-in.org/download/market/2004market.pdf>, 2004). The pollution of these sites could have resulted from any of the following: unintentional spillages; blatant disregard to existing waste management regulations; and outdated waste disposal practices, when there was little or no regulation as to how and/or where to dispose (Roberts, J. 2009). Regardless of the cause or source of pollution, once it is discovered, prompt action is required by law to contain the source of pollution and clean up the polluted site.

It is usually at this stage that organizations or individuals responsible for the pollution begin to develop and compare remediation techniques, usually based on cost and effectiveness. This process of developing and comparing remediation techniques may involve the type of formal analyses that will be discussed in this thesis.

The study area presented in this report is an existing 1.6 acre landfill, owned by Oklahoma State University (OSU) that served as a hazardous/radioactive waste burial site for twenty one years. Since its decommissioning in 1980, in compliance with newer regulations, the Oklahoma Department of Environmental Quality (ODEQ) demanded that proper site closure procedure be performed for the site. In response to this demand, OSU initiated the process in the late 1980s.

Since the closure process was initiated, twelve groundwater monitoring wells have been constructed on the site (Figure 2-2) and periodic groundwater samples have been collected from them and tested for contamination. Test results indicated small concentrations of volatile organic compounds (VOCs), semi volatile organic compounds (SVOCs), metals, and low level radioactive substances (2009 Second Quarterly Reports, Fox *et al.*, 2009). With the assertion that the site was contaminated, appropriate remediation planning followed, aimed at completely removing or adequately containing the contaminants and their sources, and to ensure that the site does not pose any present or future threat to the human health and/or the environment.

In this project, a decision making technique that was originally developed for solving business related problems, was adapted to the remediation planning stage of the site closure process. Application of this methodology to environmental and natural science problems can be traced back to 1981, when Freeze and his colleagues applied the same

principle to hydrogeological decision analysis. Since then, other scientists such as Wang et al. (1998) and Wang and McTernan (2001) have applied the same methodology to environmental decision making.

Why Decision Models?

In reality, people are rarely faced with simple “yes or no” questions; instead, we are confronted with situations that require analyzing a variety of factors before arriving at a solution. The more complex a problem, the more complicated the decision, and keeping track of all the influencing factors can add significant uncertainties to the decision process. Therefore, any well structured system, such as a model, that can help keep all these contributing factors in view will be helpful. Decision models are used to improve the accuracy of decision making beyond a human expert’s interpretative ability, thus improving the management of any given system (Murphy, P., 1996).

Common Decisions Making Conditions

It is difficult, if not impossible, to enumerate every condition likely to be encountered by decision makers when making a decision, however, they can be divided into three broad categories, according to Rosenhead *et al.* (1972) as decision making under conditions of certainty, risk and uncertainty.

1. Under conditions of *Certainty*, all the parameters are deterministic and completely known to the decision maker (Snyder, L. V., 2006).
2. Under conditions of *Risk*, not all the parameters are completely known, but the values of the unknowns can be determined using principles of probability that are known to the decision maker. Problems in this category are known as stochastic optimization problems, and the goal here is to optimize the expected value for some objective

function (Snyder, L. V., 2006).

3. Under conditions of *Uncertainty*, not only are the parameters unknown, but also their values cannot be determined stochastically. Problems in this category are called robust optimization problems, and solutions are aimed at optimizing the worst case performance of the system (Snyder, L. V., 2006).

Most engineering projects, such as the one reported in this thesis rarely fall into the certainty category, but rather tend to involve elements of risk and/or uncertainty. It is therefore pertinent that methodologies designed to address such problems account for both risk and uncertainty conditions.

Decision Tree Model

Decision models involving risk and uncertainty can either be in matrix form or as a network of nodes called a decision tree (White et. al, 2009). Irrespective of the format, the objective is to simplify the decision making process. Similar research as that reported in this thesis have employed the decision tree methodology because it provides a convenient way to visualize the decision model and methodology. Wang *et al.* (1998), and Wang, T. A. and McTernan, W. F. (2001) applied the principles of decision modeling to optimize groundwater remediation design. Similarly, efforts by Freeze *et al.* (1990) and Massmann *et al.* (1991) used decision analysis in engineering design projects that involved hydrogeologic components.

The decision analysis methodology reported here links a decision model to results from cost estimating and spatial mapping programs and then displays the model in decision tree format. A simplified decision tree is illustrated in Figure 1-1 where there are three distinct kinds of nodes:

1. Square nodes (or decision nodes) indicate that a decision is to be made among the

alternative branches emanating from that node (DATA 2.0, 1994).

2. Circular nodes (or chance nodes) precede the uncontrollable states of nature that are likely to occur (DATA 2.0, 1994).
3. Triangular nodes (or Terminal node), indicating the end of a decision path or scenario (DATA 2.0, 1994).

Branches connecting a decision node to a chance node represent alternatives to be selected from, and branches between the chance nodes and terminal nodes represent the uncontrollable states of nature (Ossenbruggen, 1984).

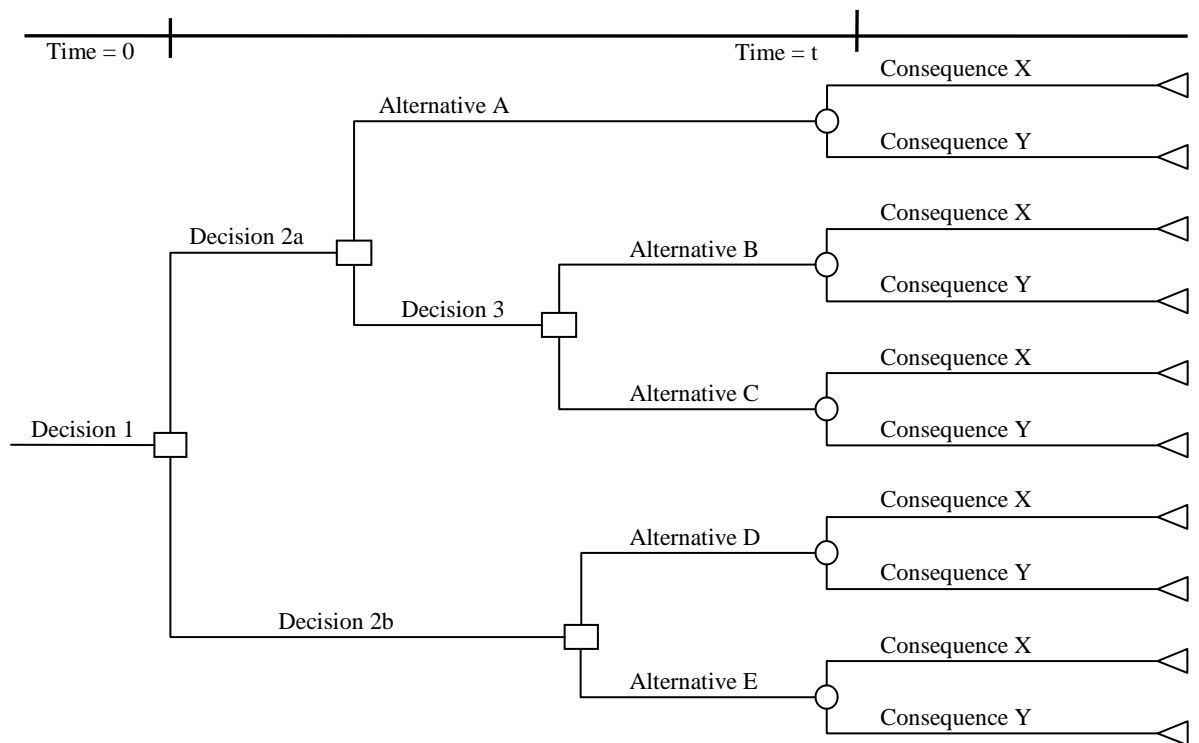


Figure 1-1: Simplified decision tree structure showing types of nodes, decision alternatives and paths (Source: Wang 1998)

Decision Making Methodology Adopted

Several decision making methodologies are available in the literature, but for the purpose of this analysis, the five (5) step decision making process described by B.F. Baird in 1978, shown in Figure 1-2 below, was adopted. In the first step of the process, “Define problem”, the decision maker identifies and states the overall objective of the analysis in a clear problem statement or phrase. This step is crucial because the initial and desired conditions are established, without which progress to the next step will not be possible (Janos, F., 2009). The second step, “List Alternatives”, offers different approaches for changing the initial condition to the desired condition. It is at this stage that alternatives are screened initially and the unattainable eliminated from further consideration (Janos, F., 2009). Step 3, “Define Criteria” is the stage in the process where the conditions for screening or discriminating among alternatives are defined. It is necessary to define discriminating criteria as objective measures of the goals to measure how well each alternative achieves the goals (Janos, F., 2009). Step 4, “Evaluate Alternative” involves analyzing, and ranking the alternatives according to the criteria defined in step 3. Finally, step 5, “Selection of the Best Alternative”, is the stage where the highest ranked alternative is selected based on the evaluation carried out in step 4.

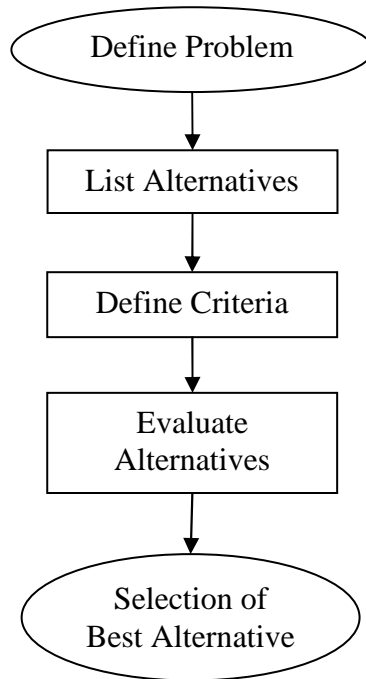


Figure 1-2. Decision making process as stipulated by Baird, 1978

For different problems, the method(s) by which the steps mentioned above are achieved vary, and may require the use of mathematical and statistical tools, computer models, experiments, and other means of data collection and analysis; but more importantly, the reliability of the outcome depends on the skills and experience of the decision maker. The following chapters of this report will introduce the contaminated site problem, and discuss the procedures that were undertaken in performing a decision analysis to determine the most cost effective remediation alternative for cleaning-up the contamination problem. The outcomes and recommendations of the decision analysis are also presented and discussed.

CHAPTER II

REVIEW OF LITERATURE

Overview of Study Area

The decision making methodology developed by this effort was used to design a remediation plan for an existing contaminated site. Site data used in the analysis were obtained from old site survey data, site closure documents and recent site assessment information. The site, a former hazardous waste landfill operated by the Oklahoma State University (OSU), served as a low-level radioactive and chemical waste burial site from 1959 to 1980 (OSU WBSDP Document, 1996), and is located on a 1.6+ acre property belonging to OSU in the NW ¼ NE ¼ NW ¼ Section 2, Township 18 North, Range 1 East, Payne County, Oklahoma (OSU WBSDP Document, 1996). Figure 2-1 shows the geographical location of the site within Payne County, and the inset map at the top left corner of the figure shows the Payne county location within Oklahoma. The figure shows that the site is located on west 44th street.

Low-level radioactive waste was first buried in the site in 1959 under radioactive material license number – NRC 35-00237-03 (previously AEC 35-00237-02), and last buried on December 31, 1980 (OSU WBSDP Document, 1996). Chemical wastes was first buried in 1973 in a different area than the radioactive waste, and last buried in 1980 (OSU WBSDP Document, 1996).

Available data show that radioactive and chemical wastes were buried in various containers, including: glass bottles, plastic bottles and bags, metal cans and drums, cardboard boxes, and paper sacks. Others were just buried without any container. The wastes were buried in trenches excavated using a tractor mounted backhoe at depths not exceeding twelve feet (OSU WBSDP Document, 1996).

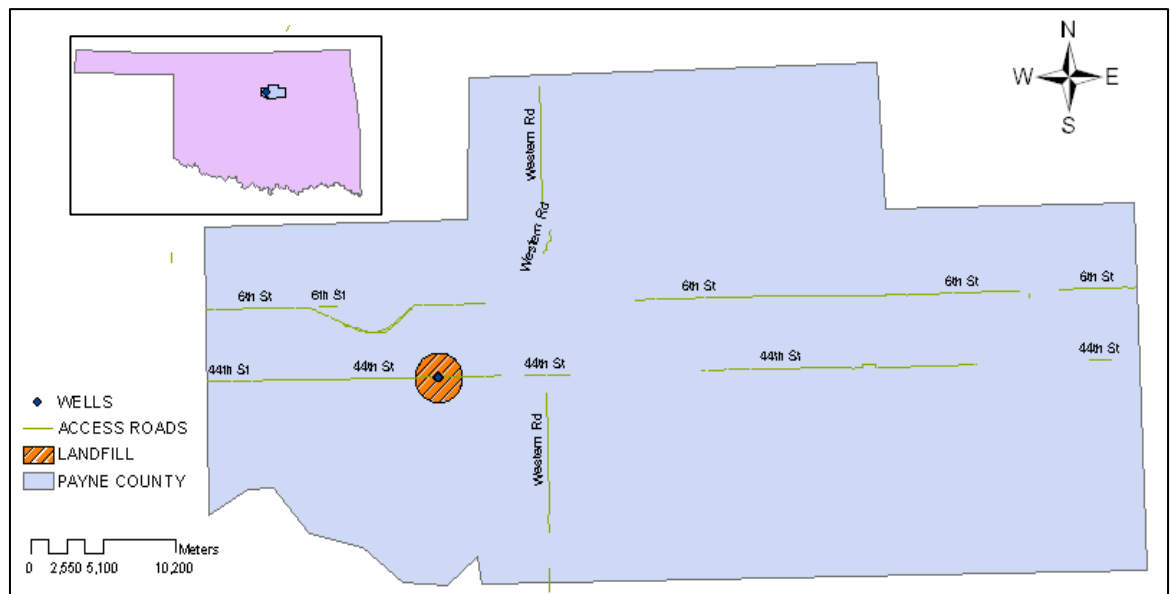
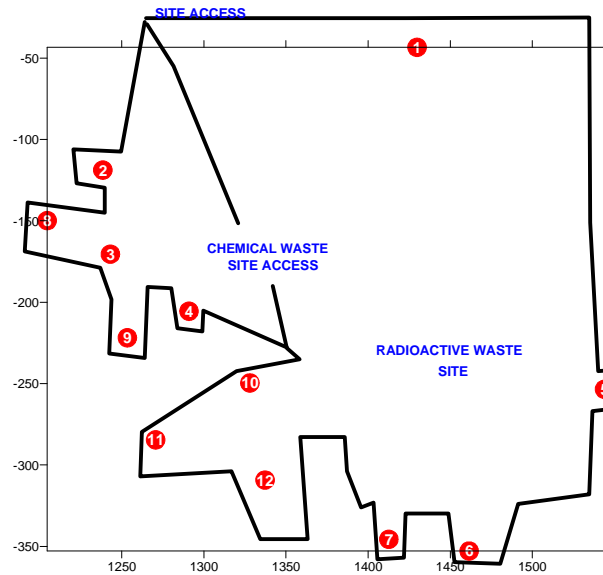


Figure 2-1: Site Location in Payne County, with Inset showing Location in Oklahoma

Twelve monitoring wells previously constructed and situated around the site, as shown in Figure 2-2, were sampled and tested for several months. The test results confirmed the presence of contamination in the groundwater.



- Coordinates are distance (in ft) from a reference location

Source: Fox G. et al, 2009

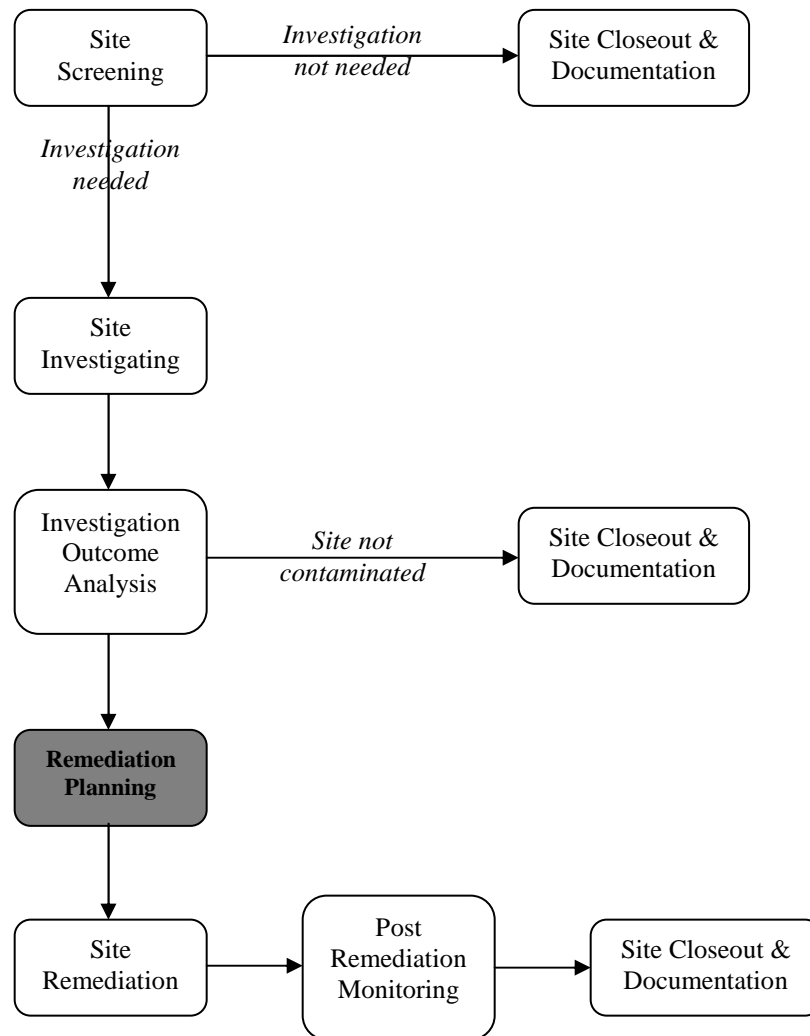
Figure 2-2: Site plan of former OSU burial site showing the monitoring wells

Although several contaminants were detected in the area, only three chemicals and one radioactive material were selected and used for analysis for this thesis. The contaminants selected for the decision model were those with the highest observed concentrations and the highest number of measurements over the site. For this thesis, we assumed that by addressing these contaminants, those occurring with less frequency or at lower concentrations would also be subject to the remediation approaches evaluated.

Remediation Planning Process

The flow chart shown in Figure 2-3 illustrates the stages involved in developing a remediation plan for a contaminated area. Each arrow represents a unique stage in the process. This type of conceptual model is needed to preliminarily qualify the available information prior to the construction of the formal decision model. This thesis is centered on the “Remediation Planning” stage of the flow chart shaded below, and presents the

methodologies and results obtained from developing a plan for the existing OSU site.



Source: Ministry of Environment British Columbia, 2009

Figure 2-3: Flowchart showing stages of remediation

Toxicity of Selected Contaminants

As mentioned earlier, three chemical contaminants trichloroethene (TCE), 1,2-dibromoethane (EDB), and chromium; and one radioactive contaminant, gross alpha were selected for this analysis. One of the bases for selecting these contaminants was their known hazards to human health and the environment. Information from the U. S.

Environmental Protection Agency Ground Water and Drinking Water Factsheets

(<http://www.epa.gov/safewater/hfacts.html>, Nov. 2008) and the Idaho National

Laboratory database (<http://www.stoller-eser.com/FactSheet/alpha.htm>, Nov. 2009) were used for these determinations.

A. Trichloroethene (TCE)

(<http://www.epa.gov/safewater/pdfs/factsheets/voc/tech/trichlor.pdf>, Retrieved Nov. 2008):

1. *Physical Properties:* TCE is a colorless or blue organic liquid with a chloroform-like odor. The greatest use of TCE is to remove grease from fabricated metal parts and some textiles. TCE is a highly volatile pollutant that evaporates rapidly when released to the environment. If it is released to the soil it will either evaporate completely or migrate to groundwater; it also evaporates quickly when released in water, with a moderate likelihood of accumulating in aquatic animals.
2. *Source & Statistics:* The main source of TCE pollution to the environment is emissions from metal degreasing plants. Other sources are wastewaters from processes such as metal finishing, paint and ink formulation, electric/electronic components, and rubber processing industries.
3. *Regulation:* The Safe Drinking Water Act of 1974 required EPA to set the Maximum Contaminant Level Goal (MCLG) for TCE in drinking water. The MCLG is a non-enforceable standard that is based solely on possible health risks and exposure. For TCE, the MCLG is set as zero, because that level of protection would not cause any of the potential health problems caused by TCE. Based on this MCLG, an enforceable standard known as the Maximum Contaminant Level (MCL), has been set at of 5µg/l by the EPA considering the ability of public water

systems to detect and remove contaminant using suitable treatment technologies.

4. *Health Effects:* Extended exposure to TCE in concentration in excess of 5µg/l can have severe health effects including acute liver problems and increased cancer risk.

B. 1,2-Dibromoethane (EDB)

(<http://www.epa.gov/safewater/pdfs/factsheets/soc/tech/edb.pdf>, Retrieved Nov. 2008):

1. *Physical Properties:* EDB is a colorless, heavy organic liquid with a mildly sweet chloroform-like odor (US EPA Factsheet on EDB, Nov. 2008). It is mainly used as an anti-knock mixture in gasoline, especially aviation fuel. It is also used as a solvent for resins, gums, and waxes; in waterproofing preparations; in dyes and drugs production; and as a pesticide in crop cultivation. EDB was used at OSU as a pesticide in research.

EDB pollution can either be due to spillage or during soil fumigation. If it is released to land, it migrates to groundwater, and depending on the type of soil, its persistence may vary from just a few weeks to as long as 19 years or even more. Chemical reactions and microbial activities in some types of groundwater can degrade it as well. When released in water, most of it will evaporate, with a significantly low likelihood of accumulating in aquatic life.

2. *Source & Statistics:* EDB is released during the use, storage and transport of leaded gasoline, as well as during any spills; from its former use as pesticides, wastewater and emissions from processes and wastewaters of chemical industries that use it (US EPA Factsheet on EDB, Nov. 2008).

The source of EDB contamination at the OSU site may have been as a result of by-products of pesticides used for various purposes at the time of and prior to waste disposal at the site.

3. *Regulation:* The Safe Drinking Water Act of 1974 sets the MCLG for EDB at zero. Based on this MCLG, the MCL for EDB is set by the EPA at 0.05µg/l, taking into consideration the ability of public water systems to detect and remove contaminant using suitable and available treatment technologies.
 4. *Health Effects:* Short term exposure to EDB at concentrations greater than the MCL can have adverse health effects such as: damage to the liver, stomach, adrenal glands, and significant reproductive system toxicity especially the testes. Long term exposure to EDB high concentrations also can potentially damage the: respiratory system, nervous system, liver, heart, and kidneys, and significantly increases cancer risks.
- C. Chromium (<http://www.epa.gov/safewater/pdfs/factsheets/ioc/chromium.pdf>, Retrieved Nov. 2008):
1. *Physical Properties:* Chromium is a metal found in natural deposits as ores containing other elements. It is abundant in nature with a valence state ranging from -2 to +6, however, in the natural environment it either exists in its trivalent (Cr(III)) or hexavalent (Cr(VI)) form (US EPA CLU-IN: Chromium VI overview, 2004). Small amounts of trivalent chromium occur naturally in food items and are often recommended as a dietary supplement. Hexavalent chromium is the form responsible for environmental pollution.

Chromium has numerous uses; the most common and most important ones

being for producing metal alloys such as stainless steel; protective coatings on metals; magnetic tapes; and pigments of paints, paper, rubber, composition of floor covering and other materials. Its soluble forms are used in wood preservation (US EPA Factsheet on Chromium, Nov. 2008). Presence of chromium at the OSU site is attributable to leachates from chrome-plated parts of the installed wells or deposits from previous uses as a deterrent for hard water deposition on cooling water pipes and boilers.

2. *Source & Statistics:* In the US soils alone, the concentration of naturally occurring Cr(VI) ranges from 1 to 2000ppm, with a much lower concentration in air (0.01 to 0.03 $\mu\text{g}/\text{m}^3$) due to its ability to react with other pollutants in the air to form Cr(III) (US EPA CLU-IN: Chromium VI overview, 2004). When chromium is released to land, its compounds bind to soil and are unlikely to migrate into groundwater. They persist as sediments in water and have a high potential to accumulate in aquatic life (US EPA Factsheets on Chromium, Nov. 2008).
3. *Regulation:* The Safe Drinking Water Act of 1974 sets the MCLG for chromium at 0.01 mg/l. The EPA has established a MCL of 0.1 mg/l for chromium.
4. *Health Effects:* short term exposure to chromium at levels greater than the MCL may skin irritation or ulceration. Long term exposure to EDB can potentially damage the: liver, kidney circulatory, and nerve tissues; and skin irritation (US EPA Factsheets on Chromium, Nov. 2008).

D. Gross Alpha (<http://www.stoller-eser.com/FactSheet/alpha.htm> Retrieved Nov. 2009):

1. *Physical Description:* Gross alpha radioactivity analysis is the measurement of all

alpha radiation present, regardless of the radionuclide source. Alpha particles are a type of ionizing radiation ejected by the nuclei of some unstable atoms. They have two protons and two neutrons and are relatively heavy, high-energy particles with a positive charge of +2 from the two protons. The velocity of alpha particles in air is approximately one-twentieth the speed of light (Idaho National Lab., Nov. 2009).

Alpha particles are emitted when the ratio of neutrons to protons in the nucleus is too low. The atoms try to restore the balance by emitting alpha particles. Alpha emitting atoms tend to be large atoms and can be either naturally occurring or manmade elements. Examples include Americium-241, Plutonium-236, Uranium-238, Thorium-232, Radium-226, Radon-222, and Polonium-210 (Idaho National Lab., Nov. 09).

2. *Alpha Emission and the Environment:* Most alpha emitters occur naturally in varying amounts in nearly all rocks, soil and water. Human activities, however, also increase or worsen the potential for exposure of people to contamination of various environmental media. An example of such anthropogenic activities is uranium mining waste (known as uranium tailings) that has a high concentration of uranium and radium, which once brought to the surface can become airborne or enter surface and/or subsurface water. Mining and processing of phosphate for fertilizer is another human activity that can result in significant alpha particle emission (Idaho National Lab., 11/05/09). In the case of the study area, most of the gross alpha emitters detected in the area were markers used for research purposes during the active years of the landfill.

Once emitted into the environment, alpha particles move relatively slowly, in comparison to beta (two-third the speed of light) or gamma (speed of light) particles and they do not travel far due to their electric charge and large mass. They lose energy rapidly in air, usually within a few centimeters, and because alpha particles are not radioactive once they have lost their energy, they pick up free electrons and become helium (Idaho National Lab., Nov. 2009).

3. *Health Effects*: Depending on the exposure route, whether external exposure or internal exposure, the effect of alpha emission to health can vary. If the exposure is external then there is minimal health concern, because alpha particles are incapable of penetrating the outer dead layer of the skin. However, if the particles are inhaled or ingested, or absorbed into the blood stream, sensitive tissues can be damaged, thereby increasing the risk of cancer. Alpha particles in particular have been known to cause lung cancer in humans. For the average citizen, exposure to radon and its decay products is the major source of exposure to alpha radiation.

Remediation Techniques Considered

Hazardous wastes are often treated to either reduce the total volume of waste to be disposed or to reduce the toxicity, thereby ensuring the protection of human health and the environment. These remediation objectives, depending on the problem at-hand, can be achieved via many clean-up techniques, it is therefore important that techniques selected in any situation is capable of achieving treatment goals. In this case study, a computer-based program, RACERTM, developed by the United States Air force and recommended by the Environmental Protection Agency (EPA) was used to generate and access remediation techniques. For the contaminated site problem discussed in this thesis,

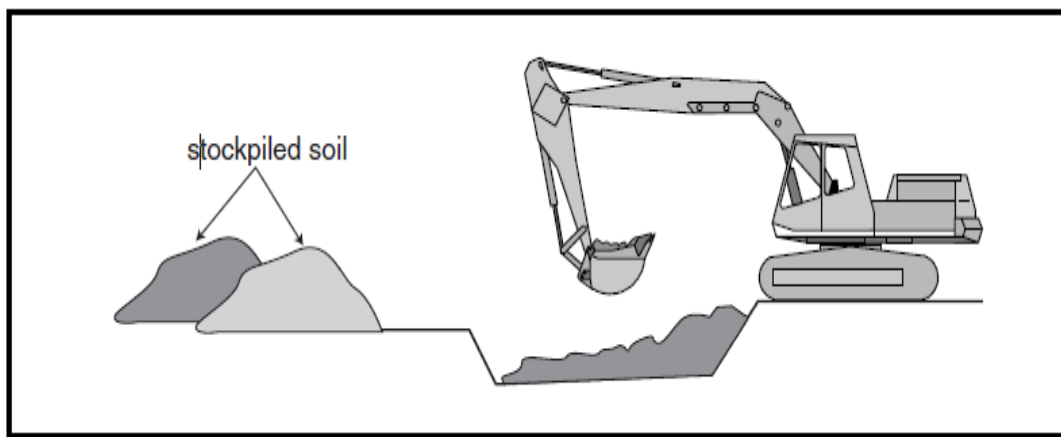
five remediation techniques, namely excavation, capping, slurry wall installation, soil washing, and monitored natural attenuation, were assessed and compared based on cost of implementation and completion.

(1) Excavation

Excavation is a remediation technique used to remove contaminated material from a hazardous waste site with the use of heavy construction equipment, such as bulldozers, front loaders, and tipper trucks (EPA Fact Flash 8, Jun. 2009). Figure 2-4 illustrates a simple schematic of the excavation process. The first step in excavation is to identify and map out the contaminated area to be excavated. Several techniques can be employed to achieve this, including soil sampling, a technique where samples are collected at varying depths in the same location, both vertically and horizontally, so that a contaminant concentration map can be established. Historical records, site documents, and eye witness accounts, photographs and physical effect of contaminants on plants can also be as used to identify areas to excavate (EPA Fact Flash 8, Jun. 2009).

Once the area to be excavated has been identified, the next step is to commence excavation. Occasionally, the layer of soil overlaying the hazardous materials (called the overburden) is first carefully removed and stored, then replaced after the contaminated materials have been dug-up. The excavated waste is then loaded onto a truck and hauled to an appropriate disposal location either to be landfilled, or treated. Treated soil can be returned to the site and used as backfill. Soils in the walls and bottom of the excavated area are tested to ensure that all contamination has been

removed. Excavation proceeds until cleanup goals are met (EPA Fact Flash 8, Jun. 2009). This technique has been found to be highly versatile in its applicability, and is capable of treating a wide variety of waste types. However, concerns for workers health and safety may prevent excavation of explosives, reactive or highly toxic materials (US DOE).



EPA/Clu-IN: A Citizen's Guide to Excavation, 2001

Figure 2-4: Simple illustration of excavation process

(2) Capping

Unlike excavation, where the contaminants are removed, capping techniques leave the contaminated materials on site. It is used when the contaminated area is so vast that excavating and disposal is practically impossible or extremely uneconomical, when removing the waste would be more dangerous to human health and the environment than leaving it in place, where the waste is too deep to be economically excavated, mixed hazardous-radiological wastes occur, which can have unique problems and higher remediation costs. Caps are used to cover buried wastes and to minimize/eliminate contaminant migration as a result of surface water or rainwater movement through a site or wind blowing over the site. Caps are usually

made up of a combination of materials such as synthetic fibers, heavy clays, and occasionally concrete (EPA Fact Flash 8, Jun. 2009).

A properly installed cap must be able to (EPA Fact Flash 8, Jun. 2009):

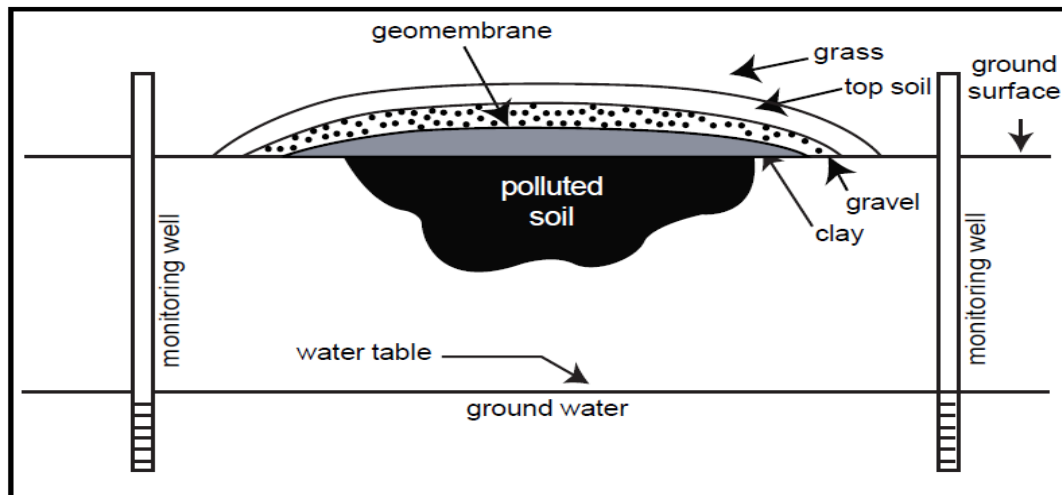
1. minimize water movement through the waste by efficient drainage,
2. resist damage caused by settling,
3. prevent standing water by funneling away as much water as the underlying filter or soil can handle, and
4. allow easy maintenance.

There are two types of caps: multi and single-layer caps (EPA Fact Flash 8, Jun. 2009).

1. The multilayered caps have three layers: Vegetation, drainage, and water-resistant. The vegetation layer prevents erosion of the cap's soils; the drainage layer channels rainwater from collecting in the water-resistant layer, which covers the waste (FRTR: 4.26 Landfill Cap, Mar. 2010).
2. Single-layer caps are made of many materials that resist water penetration. The most effective single-layer caps are made of concrete or asphalt. Generally, the wetter the climate, the more complex the capping system (FRTR: 4.26 Landfill Cap, Mar. 2010).

Figure 2-5 illustrates a multilayered cap, highlighting the salient components: the vegetation (grass) layer, the drainage (top soil) layer, and the water resistant (geo membrane) layer. Wells are included for monitoring the groundwater for movement of contaminants. Caps have been found to efficiently seal off buried contaminants from the surface environment and to reduce subsurface waste migration; they are versatile and can be applied to almost any site in a relative short period of time.

Capping materials and equipment are readily available and with proper maintenance, a multilayered cap can last longer than 20 years (EPA Fact Flash 8, Jun. 2009).



EPA/Clu-IN: A Citizen's Guide to Capping, 2001

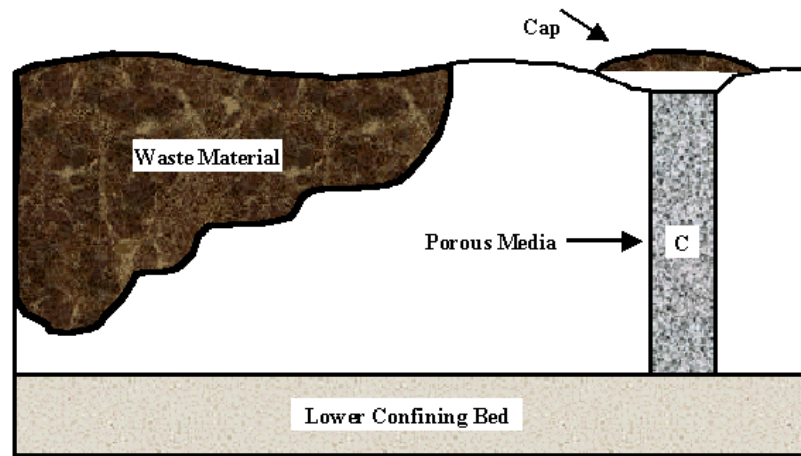
Figure 2-5: Simple illustration of capping technology

(3) Slurry wall

Slurry walls are physical subsurface barriers that can be used to contain contaminated groundwater, divert contaminated groundwater from drinking water intakes, divert uncontaminated groundwater flow, and/or provide a barrier for a groundwater treatment system (Pearlman, 1999). They typically constitute vertically excavated trenches that are filled with slurry. The function of the slurry is to prevent collapse by hydraulically shoring the trench and to form a filter cake to reduce groundwater flow (Pearlman, 1999).

Although slurry walls are stand-alone technologies that have been used for decades as long-term solution for subsurface seepage control, they have also often been used in conjunction with capping. They are best suited for situations where the waste mass is too large for treatment and where soluble and mobile constituents pose

an imminent threat to a source of drinking water (Pearlman, 1999). Figure 2-6 depicts a typical cross section of a slurry wall anchored into the subsurface.



Source: frtr.gov, 11/05/09

Figure 2-6: cross section of a typical slurry wall anchored into the subsurface

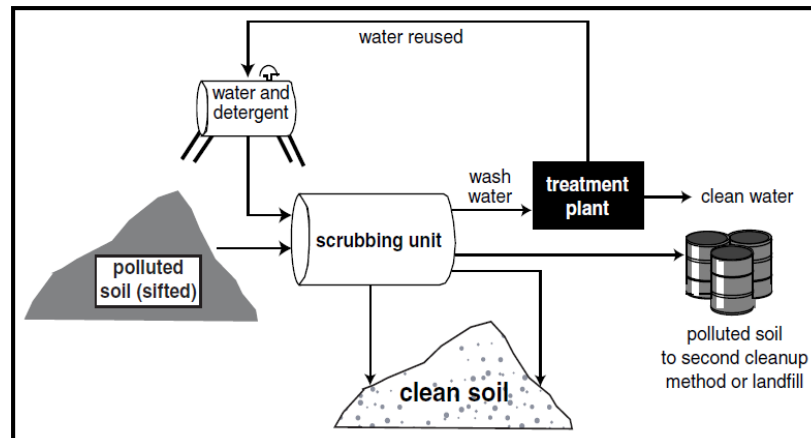
Slurry walls can be made from a variety of materials including soil-bentonite, cement-bentonite and plastic concrete (Pearlman, 1999). The backfill and composite typically contain a mixture of materials such as cement, bentonite, fly ash, ground-blasted furnace slag, and clay (Pearlman, 1999).

(4) Soil Washing

Soil washing is a remediation method that scrubs the contaminated soil to remove and separate the portion of the soil that is most polluted (Citizen's Guide to Soil Washing, 2001). It is a volume and cost reduction technique that reduces the volume of soil that requires treatment and/ or disposal, and the overall cost of the cleanup process. For example, soil washing can reduce the amount of excavated material requiring treatment or disposal by up to 87 percent (RACER 10.2, 2008).

Figure 2-7 depicts the process of soil washing. During soil washing,

contaminants are concentrated in the finer fraction of the feed soil by an aqueous based washing process. The finer particles, which contain the bulk of the contaminants, are removed and disposed, and the portion of uncontaminated soil is returned to the site and reused as backfill (RACER 10.2, 2008).



EPA: A Citizen's Guide to Soil Washing

Figure 2-7: Schematic illustration of soil washing process

(5) Monitored Natural Attenuation

Natural attenuation relies on natural processes to clean up or attenuate pollution in soil and groundwater (Citizen's Guide to MNA, 2001). The right conditions are necessary for the site to be quickly and completely cleaned up. Regular monitoring is required to ensure that natural attenuation is working, hence the name "Monitored Natural Attenuation" or simply MNA.

Four processes by which the environment attenuates contaminants have been identified and discussed below (Citizen's Guide to MNA, 2001):

- a. Attenuation by microbial digestion – This is when attenuation is dependent on microbes in the soil to feed on the chemical contaminants. Chemical processes

within the microbes transform the harmful contaminants to water and nontoxic gases.

- b. Attenuation by soil sorption – This is when contaminants are both absorbed and adsorbed by the soil. This process does not clean up the contaminants but can restrain them from entering into the groundwater.
- c. Attenuation by dilution – This process of attenuation relies on dilution of contaminants as they travel through groundwater to achieve cleanup.
- d. Attenuation by evaporation – Some chemicals can evaporate and change from liquids to gases within the soil. If these gases escape to the air at the ground surface, sunlight may destroy them.

For efficient MNA, the source of pollution must first be identified and removed through any of the available cleanup methods.

Analysis and Decision Tools Utilized

Designing a remediation plan for the contaminated site problem discussed in this text required the analysis of several parameters with the aid of computer based programs. The analyzed parameters include the geographical features like groundwater levels, the type/concentration of pollutants present, and comparison of applicable remediation techniques based on cost and efficiency. For these analyses, the following tools were used:

- (1) Surfer8™ is a contouring and surface mapping program that runs in the Microsoft Windows environment. It quickly and easily converts coordinates into contour, 3D surface, 3D wireframe, vector, image, shaded relief, and post maps (Golden Software, 2008).

(2) RACER™, an acronym for Remedial Action Cost Engineering Requirement, is a computer-based system originally developed in 1991 by the U.S. Air Force for estimating cost of environmental remediation projects. The program uses a patented methodology for generating location-specific program cost estimates and allows the user to select the desired models from a list of available technologies, define the required parameters in the selected technology, and tailor the estimate by verifying and editing secondary parameters (FRTR: RACER, 2008). RACER™ calculates quantities for each technology; localizes unit costs for materials, equipment, and labor; adjusts unit prices for safety and productivity losses; and applies markups to account for indirect costs (FRTR: RACER, 2008). RACER™ uses current multi-agency pricing data, and is researched and updated annually to ensure accuracy (FRTR: RACER, 2008).

RACER™ is applicable to several media including soil, sediment, groundwater, surface water, sludge, building materials, ambient/indoor air, and free product (Claypool, 2009). The system covers a wide range of regulatory programs also, including CERCLA/Superfund, RCRA Corrective Action, State Groundwater Protection Programs, State Voluntary Cleanup Programs, Radioactive/Nuclear Facility D&D, Abandoned Mine Lands Programs, Military Munitions/Unexploded Ordnance Programs, and Non-U.S. Cleanup Programs (Claypool, 2009). It is designed to address all the stages of a remediation exercise, namely Pre-study, Study, Removal/Interim Actions, Design, Construction/Implementation, Operation & Maintenance, Long-term Monitoring and Site Closeout (Claypool, 2009). RACER™'s ability to provide comprehensive documentation and auditable and

defensible records of all input parameters, assumptions and notes used in building the estimates makes it a tool of choice for numerous users, including private corporations, engineering/consulting firms, state environmental regulators, law firms, insurance underwriters, and government agencies (Claypool, 2009).

- (3) Decision Analysis by TreeAge (DATATM) is a computer program that implements the principles of decision analysis through a consistent, logical, user-friendly interface (DATA, 1996). Decision analysis is the discipline of evaluating complex alternatives in terms of values and uncertainty (Arsham, 2009). Often, values are expressed monetarily because this is a major concern for management and numbers are used to quantify the uncertainties (Arsham, 2009).

DATA uses a tree structure (see Figure 1-1) to link the possible chain of events (decisions, chance events, and final outcomes) into a clearly specified sequence of events. The decision tree structure is discussed in detail in Chapter 1 of this report.

Waste Categorization and Classification

As mentioned in preceding sections of this chapter, two broad categories of waste were detected in the study area – chemical and radioactive wastes. Available waste disposal records indicate that these waste categories were disposed at different locations on the site (see Figure 2-2), but soil and groundwater samples taken around the area indicate their occurrence at the same locations. Two waste categories may also be applied to this analysis based on waste handling, disposal and treatment method, namely single waste and mixed waste treatment. At the time of this effort it was unknown whether this site would be classified by the Oklahoma State Department of Environmental Quality (ODEQ) as having these types of mixed wastes.

Single waste treatment refers to remediation design based on available technologies applicable to either one of the waste categories only – chemical or radioactive. This approach, however, may not be suitable for the study area if it was later declared to contain mixed wastes. The second classification, mixed waste treatment, refers to remediation design based on the selection of waste handling techniques and remediation technologies capable of treating both categories of waste simultaneously.

In the following chapters, the methods and methodologies adopted in this thesis analysis will be presented. Also, results and outputs from the analysis will be discussed, followed by the interpretation of the results and a conclusion.

CHAPTER III

METHODOLOGY

Selection of Contaminants of Concern

At the onset of the groundwater analysis, samples were taken and analyzed monthly, but after one quarter of sampling, the frequency of sample collection and analysis was changed to a quarterly cycle. The analysis presented in this thesis report is based on the 2009 second quarter (March through May) test results. This data subset had the most entries and the highest chemical concentration observed.

Site burial records of the OSU Landfill (OSU WBSDP Document, 1996) and groundwater sample-test results (2009 Second Quarterly Report, Fox *et al.*, 2009) both agree that the chemicals present on site generally fall into the broad categories of either volatile organic carbons (VOCs), semi-volatile organic carbons (SVOCs) or some low level radioactive substances. So, for the purpose of developing a decision tree to compare remediation alternatives based on implementation cost, three substances were selected as the contaminants of concern (CoCs), namely trichloroethene (TCE), 1,2-dibromoethane (EDB) and chromium. The selection of these substances was based on the observation that they were the most frequently occurring substances tested in the majority of the 12 monitoring wells present on the site and at quantities higher than the water quality standard in some cases.

Also, among the detected radioactive materials, the most ubiquitous substance – Gross Alpha – was selected and included in the analysis as a contaminant of concern. Gross Alpha was found to exceed the water quality standard of 15 pCi/L in the majority of the wells.

Generally, these chemicals and radioactive substances were subjected to a two phase screen before selection:

1. Availability and distribution – a good choice of CoC would be one that was present in significant amounts and was distributed around the site
2. Risk threat – the choice of CoC was one that was capable of causing significant harm to human health and environment (HH&E) according to EPA, and had information in an EPA database

The three chemicals and one radioactive substance selected as CoCs for analysis satisfied all screening criteria, because they were detected in significant quantities and were found to occur frequently in several wells. They also existed on the EPA Drinking Water Contaminants database (www.epa.gov/safewater/dwh/c-ioc.html, Nov. 2008) as chemicals capable of posing significant threats to HH&E when present in concentrations higher than the maximum contaminant level.

Table 3-1 is a list of the CoC concentrations detected from the groundwater samples as found in the 2009 second quarterly Oklahoma State University (OSU) report prepared by Fox, *et al.* (2009) to the Oklahoma Department of Environmental Quality. These data were used to create concentration contour maps (Figures 3-1 to 3-4), and the maps were used to estimate the probabilities of occurrence of the states of nature. The methodology for estimating these probabilities is described in the appropriate continuing section of this

thesis.

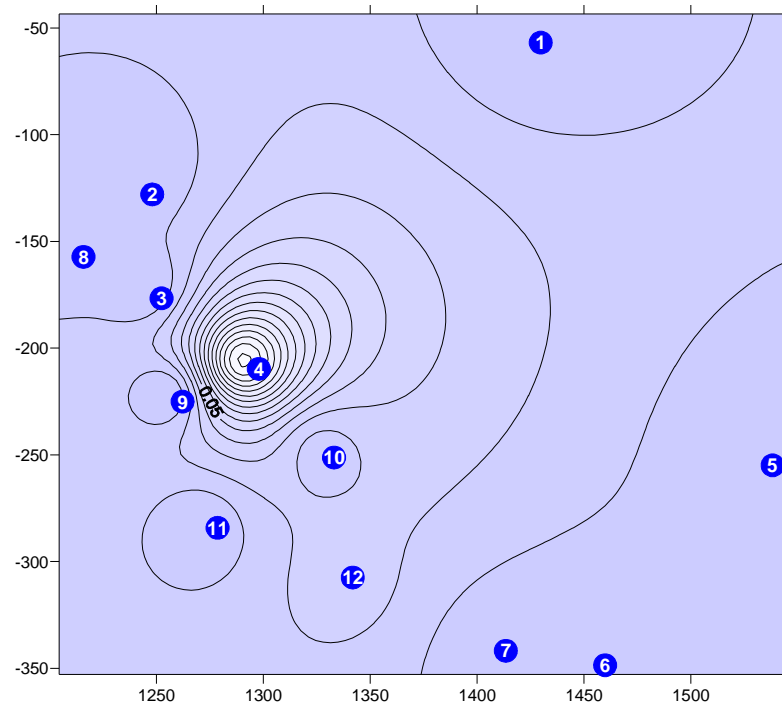
In Table 3-1, entries labeled BPQL (below practical quantification limits) indicate that CoC concentration at that well could not be measured because it occurred at such a low concentration that available laboratory techniques cannot measure it. It is, however, no guarantee that the contaminant was completely absent at that location.

Table 3-1: Concentrations of CoCs for third quarter of 2009 used for plotting contaminant distribution maps

Well #	Trichloroethene - TCE (mg/L)	1,2-Dibromoethane - EDB (mg/L)	Chromium (mg/L)	Gross Alpha (pCi/L)
1	0	BPQL	BPQL	15.8
2	BPQL	BPQL	BPQL	1.81
3	BPQL	BPQL	BPQL	22.4
4	0.153	3.24	0.411	23.8
5	0	0	BPQL	14.5
6	0	0	0.012	20.8
7	0	0	BPQL	15.2
8	0	0	BPQL	26.5
9	BPQL	BPQL	BPQL	3.03
10	0.0151	0.0214	0.013	12.4
11	0	0	BPQL	17.9
12	0.0223	0	BPQL	26.4

Source: Quarterly Report: Groundwater Monitoring Program at the OSU Burial Site, Payne County, Oklahoma, March 2009 through May 2009

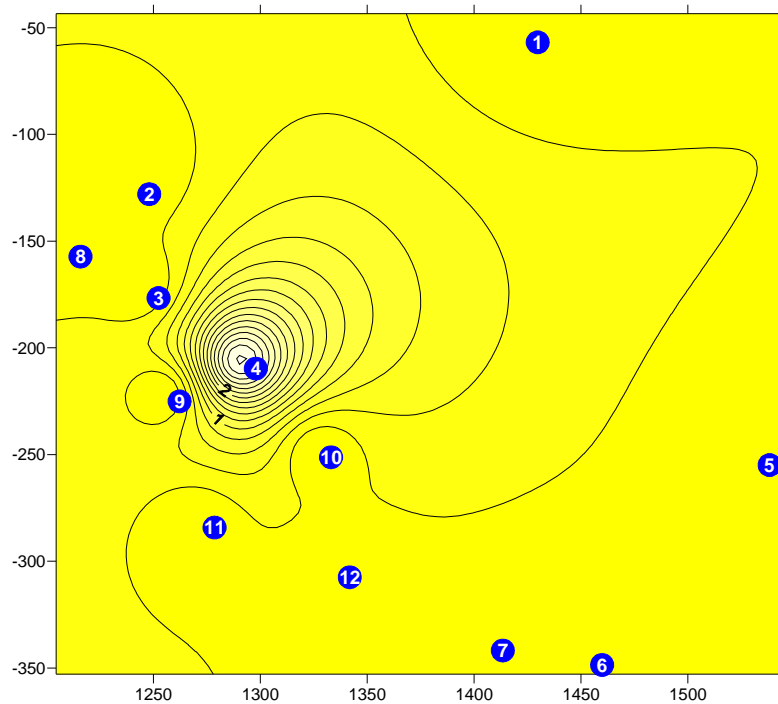
- *BPQL : Below Practical Quantification Limits*



Notes

- The dimension on each axis represents the distance in feet from an arbitrary survey point
- Each contour line represents 0.01mg/L

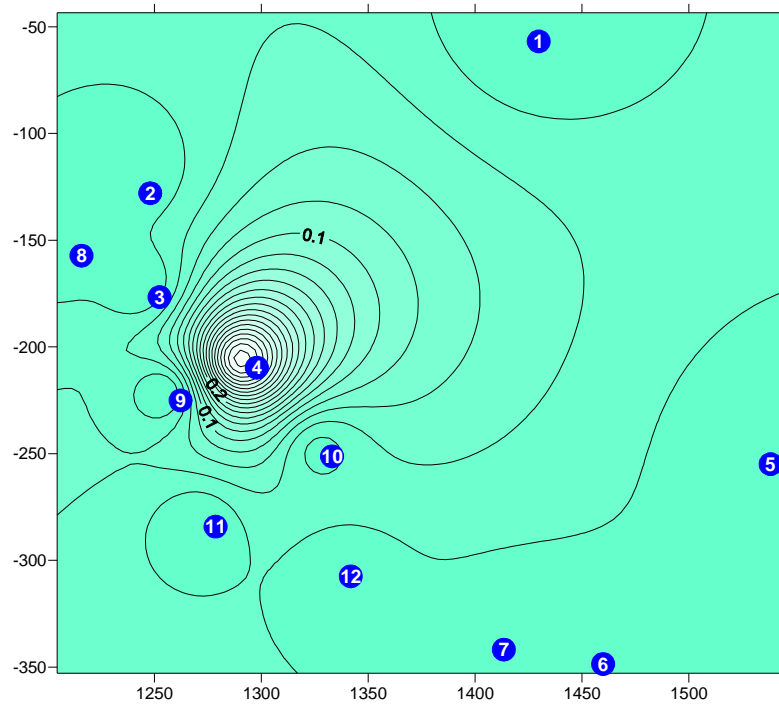
Figure 3-1: Plot of monitoring wells coordinates from an established reference point, showing the estimated TCE distribution around each well



Notes

- The dimension on each axis represents the distance in feet from an arbitrary survey point
- Each contour line represents 0.02mg/L

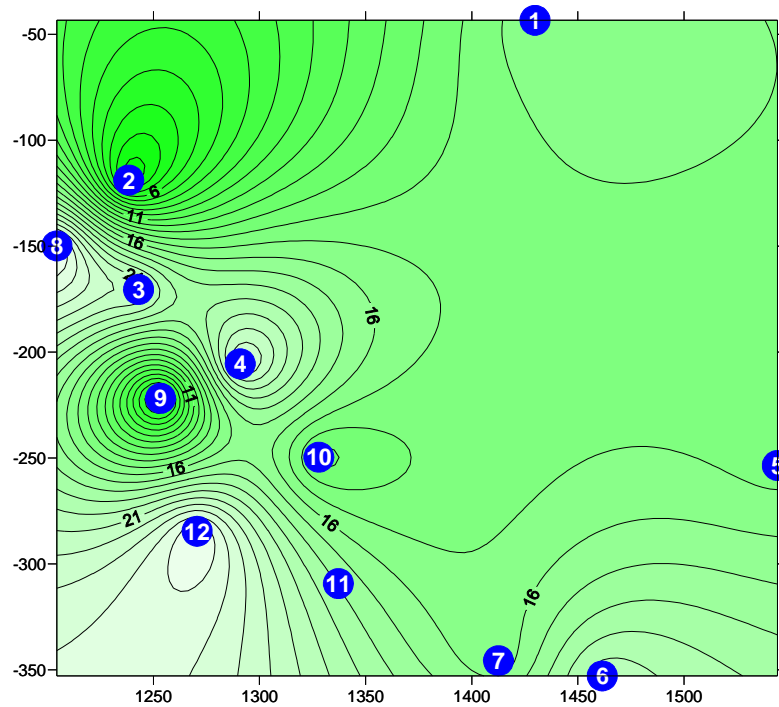
Figure 3-2: Plot of monitoring wells coordinates from an established reference point, showing the estimated EDB distribution around each well



Notes

- The dimension on each axis represents the distance in feet from an arbitrary survey point
- Each contour line represents 0.02mg/L

Figure 3-3: Plot of monitoring wells coordinates from an established reference point, showing the estimated chromium distribution around each well



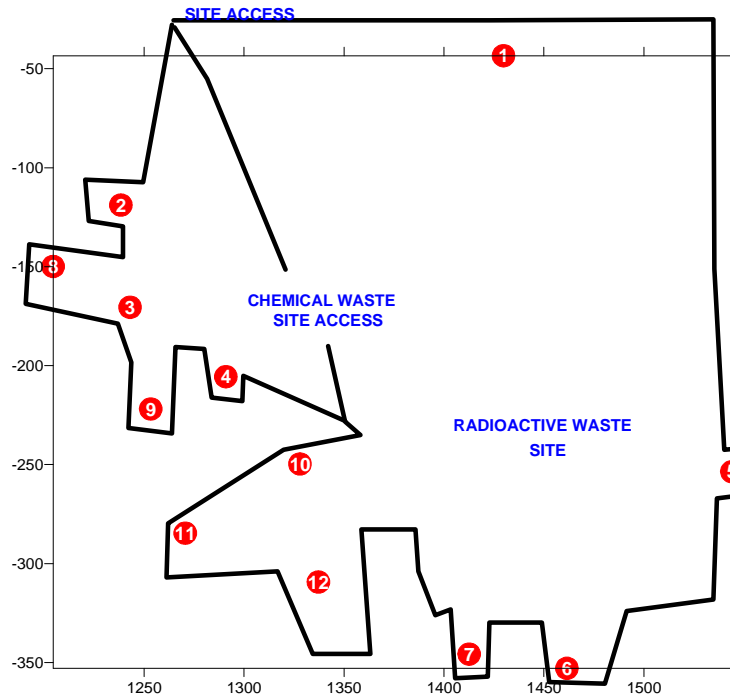
Notes

- Coordinates on each axis are distance in feet from an arbitrary survey point
- Each contour line represents 1PCi/L

Figure 3-4: Plot of monitoring wells coordinates from an established reference point, showing the estimated gross alpha distribution around each well

Management Area

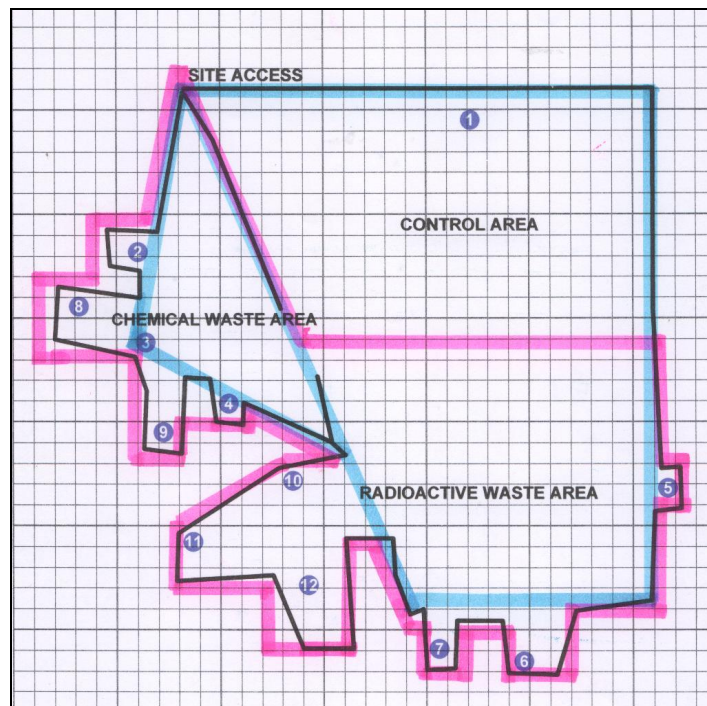
The management area, for the purpose of this project, was taken as the area upon which both actual burial of chemical and radioactive waste occurred during the active years of the landfill. This also includes areas bounding the monitoring wells bordering the burial area (MW 2 to MW 12), but excluding the control area and control well (MW1). Previous site records reveal that the monitoring wells 2 to 12 were installed such that they bordered the perimeter of the burial area as shown in Figure 3-5, except MW1 which was installed as a control in the north-eastern corner of the site. For ease of analysis, the management area (Figure 3-6) was defined such that it encompasses all the monitoring wells bordering the perimeter of the burial area. The figure shows the chemical area, radioactive area and control area; separated by distinct boundaries. The actual burial site area (blue border line) is about 1.6 ac, the management area (pink border line) is estimated to be 1.35 ac, and the black boundary line represents the existing fence lines on the site. The chemical and radioactive areas (labeled appropriately) are 0.48 ac and 0.87 ac, respectively. The well locations are as seen on the figure.



Notes

- Coordinates on each axis are distance in Feet from an arbitrary survey point

Figure 3-5: Study area map showing location of monitoring wells and other important features



Scale

- 1 grid length = 13.2 Feet
- 1 grid = 0.004 Acres

Figure 3-6. Study area map showing demarcation of management area (chemical and radioactive waste areas) from the control area

States of Nature Definition

According to Ossenbruggen, those naturally occurring events over which an engineer has no control of are referred to “states of nature” or “natural event” (Ossenbruggen, 1984). For this landfill contamination problem, three states of nature were defined based on the concentration of CoCs detected in the groundwater:

- a. $P(X_1)$ = Contaminant concentration < Practical quantification limit (PQL),
- b. $P(X_2)$ = Contaminant concentration > PQL and < Water quality standard (WQS) and
- c. $P(X_3)$ = Contaminant concentration > WQS.

The Practical Quantification Limit (PQL) and Water Quality Standard (WQS) values for each CoC were deduced from the quarterly reports and EPA Groundwater and Drinking Water Factsheet respectively; and are listed in Table 3-2.

Table 3-2: Practical quantifiable limits (PQL) and water quality standards (WQS) of CoCs

Name	PQL	WQS
TCE (mg/L)	0.005	0.005
EDB (mg/L)	0.005	0.05
Chromium (mg/L)	0.01	0.1
Gross Alpha (PCi/L)	1.26	15

Probabilities of State of Nature Estimation

To estimate the probabilities of occurrence of the states of nature, the outline of the management area (Figure 3-6) was overlaid on each CoC distribution map (Figures 3-1 to 3-4), and plotted on quad-ruled/grid-papers (see Figures 4-1 to 4-10). The reason for using gridded paper was to enhance area estimation by simply counting squares (areas) with concentrations falling within a state of nature, and dividing by the total management area. The plot was carefully drawn to scale and each square (grid) represents an area

approximately 0.004Ac in size.

Remediation Alternatives and Site Conditions

A crucial step in the remediation planning process is the selection of remediation technology(s) to be considered. For the remediation of the OSU Landfill, the following technologies were considered:

- a. Excavation and disposal of contaminated soils: in order to avail the site managers with multiple basis for making decisions, two excavation alternatives were evaluated:
 - 20 ft excavation: the first 10 ft excavated is saved and reused as backfill, whereas the bottom 10 ft (contaminated portion) is transported and landfilled at a licensed location. This depth was based on an assumption that a soil cover of 10 ft overlays the buried waste.
 - 30 ft excavation: as a worst case scenario, up to 30 ft of the contaminated area is excavated and transported off site to an appropriate landfill. This assumption was made for conservative purposes, to address contaminants movement deeper into the ground that may have occurred over the year.
- b. Low level radioactive material soil treatment (a.k.a. soil washing). This technology is usually preceded by excavation, and could be done either in-situ or transported to a different location when space or possibility of more contamination is an issue. In this case however, soil washing would be performed on-site after excavation.
- c. Capping the surface of the management area and installing a slurry wall around its circumference
- d. Monitored natural attenuation (MNA).

Each technology mentioned is discussed in detail in Chapter II of this report. Site-

specifics and clean-up requirements, necessary for estimating the remediation cost requirements included:

- Average depth to groundwater = 30 ft
- Average soil depth to be excavated = 30 ft
- Approximated distance to site (one-way) = 10miles
- Average well depth = 25 ft
- Site soil type most similar to Silty-Sand-Sandy-clay
- Number of existing monitoring wells = 12
- Number of existing monitoring wells within management area = 11
- Total management area = 1.35 Ac
- Total perimeter of management area = 1612 ft
- Post-excavation monitoring durations:
 - Excavation = 5 years
 - Soil washing = 5 years
 - Capping and slurry wall = 15 years
 - Monitored natural attenuation = 25 years

A complete listing of the site specifics and parameters used in thesis for analysis and cost estimation are provided in the appendix.

Three excavation options – 100%, 50% and 25% of the management area – were considered. The decision of “areas of concern” to focus the 50% and 25% excavation efforts on was determined by examining CoC distribution maps (Figure 4-1 to Figure 4-12) to identify “red-flag” areas (i.e. areas around monitoring wells with highest concentrations). Table 3-3 lists the parameters defining each excavation option according to the area to be excavated and “hot wells” or ‘wells-of-concern” (i.e. wells indicating higher concentrations of CoC).

Table 3-3: Excavation options and area of affected sites and well of concern

Option	Area (acre)	Wells-of-Concern
100%	1.35	All
50%	0.675	4,6,9,10,12
25%	0.338	4,6,9,10,12

Note:

1. *MW-1 is not included in the analysis because it is located with the control area.*
2. *For analysis based on radioactive contaminants, MW-3, MW-7, MW-8, MW-11 were included because the highest indications of radioactive contamination was found at and around those wells.*

Cost Estimation

For this model, failure of any remedial plan was said to have occurred if the concentration of CoC detected after a specified post remediation period exceeded the maximum contamination level (MCL). Based on this, two decision making scenarios were set for which objective functions were developed, namely:

1. Failure check at the completion of stipulated post-remediation monitoring period;
and
2. Failure check:
 - a. One year after excavation and soil treatment, and
 - b. Five years after installing a cap and slurry wall around the site and five years into natural attenuation monitoring program.

Formulating the Decision Objective Function

The developed objective functions were adapted from principles of engineering economics as presented in several engineering economics texts (e.g. *Systems Analysis for Civil Engineers* [by Ossenbruggen, J. P.1984] and *Principles of Engineering Economics Analysis* [by White *et al.* 2009]), and were used in this analysis to estimate the expected monetary values (EMV) for the alternative scenarios and technologies.

- Scenario I:

For this scenario, Equation 3-1a estimates the EMV for a selected remedial action without additional testing; and Equation 3-1b estimates the EMV with additional testing. The aim of these functions is to minimize the cost of remediation and the probability of failure.

$$EMV \$ = [C(t) + T(t) + M(t) + (1 + i)^t \times R(t)] \times P(Sn_x) \quad (3-1a)$$

$$EMV \$ = [C(t) + M(t) + (1 + i)^t \times R(t)] \times P(Sn_x) \quad (3-1b)$$

- Scenario II:

For the second scenario, failure cost was estimated before completion of stipulated post-remediation monitoring period. Equation 3-2a and 3-2b were the objective functions for estimating the EMV one year after excavation, with and without additional testing respectively. Equations 3-3a and 3-3b are the objective functions used in estimating the EMV five years after implementing capping and slurry wall technologies and five years after monitored natural attenuation, with and without additional testing. This scenario was introduced primarily to assess the effect of time on EMVs.

Objective Function 1 year After Excavation or Soil Treatment

$$EMV \$ = \left[C(t) + T(t) + \frac{1}{(1+i)^{t-1}} M(t) + (1 + i) R(t) \right] \times P(Sn_x) \quad (3-2a)$$

$$EMV \$ = \left[C(t) + \frac{1}{(1+i)^{t-1}} M(t) + (1 + i) R(t) \right] \times P(Sn_x) \quad (3-2b)$$

Objective Function for Capping & Slurry Wall Technology or Monitored Natural Attenuation 5years after Implementation of Technology

$$EMV \$ = \left[C(t) + T(t) + \frac{1}{(1+i)^{t-5}} M(t) + (1 + i)^5 R(t) \right] \times P(Sn_x) \quad (3-3a)$$

$$EMV \$ = \left[C(t) + \frac{1}{(1+i)^{t-5}} M(t) + (1 + i)^5 R(t) \right] \times P(Sn_x) \quad (3-3b)$$

Where	\$	=	cost in dollars
	i	=	interest rate of money
	t	=	stipulated post remediation time
	C(t)	=	remedial action cost function
	R(t)	=	risk of failure cost function
	T(t)	=	additional testing cost function
	M(t)	=	post-remediation monitoring cost function
	P(s _{n_x})	=	probability for a given state of nature

The EMV is a function of time, probability of states of nature and the prevailing interest rates. The cost functions: C(t), R(t), T(t) and M(t) were determined using RACER – a software package developed by the U.S. Air Force in conjunction with other private and public organizations that is capable of calculating the cost requirement of a remediation exercise (RACER, 2008). Each element of the cost function is described more fully below:

1. Remedial action cost function – C(t):

This function is equivalent to the capital cost of implementing a remediation technology as calculated with RACER. The remedial activities associated with the implementation of each technology are summarized in Table 3-4.

Table 3-4: Operations involved in each remediation technology

Technology Name	Remedial Activity
Excavation	<ul style="list-style-type: none"> Excavation cost Off-site transportation and waste disposal cost
Soil Washing	<ul style="list-style-type: none"> Excavation cost Soil treatment cost Off-site transportation and waste disposal cost
Capping & Slurry wall	<ul style="list-style-type: none"> Capping cost Slurry walls cost
Monitored Natural Attenuation	<ul style="list-style-type: none"> No remedial action cost involved in this operation

2. Failure cost function – $R(t)$:

This function places a monetary value on failure. As stated, the remediation program will be considered a failure if the concentration of CoC detected in groundwater samples after remediation is greater than the WQS or an alternative contaminant level acceptable to regulatory agencies. For this exercise, the cost of implementing the most extreme remediation action was taken as the cost implication for failure, which in this case was the cost of excavating up to 30 ft of the entire management area, the cost of handling, transporting and disposing the excavated material as a mixed waste, and the cost of implementing a five year post-remediation monitoring exercise on the entire site.

3. Additional testing cost function – $T(t)$:

The decision branch in Figures 3-7 and 3-8 titled “Additional Testing”, considers the cost of performing additional pre-remediation testing on the site before making the decision of whether or not to remediate.

4. Post-remediation monitoring cost function – $M(t)$:

This function provides the cost of post-remediation monitoring for a given technology and involves the cost of replacing the groundwater monitoring wells and the cost of actual monitoring for a period of time. Monitoring durations vary by technology and range from one year to twenty-five years, depending on the technology and scenario. Table 3-5 shows the technologies, and the post-remediation monitoring duration associated with each according to scenarios 1 and 2.

Table 3-5: Post-remediation monitoring durations according to scenarios

Technology Name	Scenario 1	Scenario 2
Excavation	5 years	1 year
Soil Treatment	5 years	1 year
Capping & Slurry wall	15 years	5 years
Monitored Natural Attenuation	25 years	5 years

More about RACER™

2009 dollar values of the cost functions were estimated using RACER™, a remediation cost estimating tool capable of providing preliminary cost estimates for all phases of remediation, including:

- Pre-Study,
- Study, Design,
- Removal/Interim Action,
- Remedial Action,
- Operations and Maintenance,
- Long Term Monitoring,
- Site Close-out

RACER was first released in 1991 as the result of research funded through the combined efforts of both private groups and federal government (Air Force, Army, Navy, DOE, and EPA) agencies. It has undergone several peer reviews by numerous organizations and industry professionals who have approved its applicability (RACER, 2008). Since its introduction in 1991, several other revisions and editions have been released, with the latest version being RACER 10.2, the same version adopted for this decision analysis (RACER, 2008).

RACER is a parametric cost modeling system that uses a patented methodology for estimating costs. The RACER cost technologies are based on generic engineering solutions for environmental projects, technologies, and processes. The generic engineering solutions were derived from historical project information, industry data,

government laboratories, construction management agencies, vendors, contractors, and engineering analysis. RACER advertises the most technologically up-to-date engineering practices and procedures to accurately reflect today's remediation processes and pricing (RACER, 2008).

When creating an estimate in RACER, built-in engineering solutions can be tailored by adding site-specific parameters to reflect project-specific conditions and requirements. The tailored design is then translated into specific quantities of work, and priced using current cost data (RACER, 2008). The RACER cost database is based primarily on the Unit Price Book (UPB), which was developed by the Tri-Services Cost Engineering Group (RACER, 2008). The UPB is a book that enables the construction of an accurate and dependable cost foundation, a vital requirement for the success of any project (USACE, Nov. 2009). The RACER database also includes a number of specialized assemblies that are not derived from the UPB. Costs for all assemblies in the RACER database are updated annually (RACER, 2008).

Decision Model

The intent of the decision model was to provide the decision maker with a way of concisely visualizing the problem and a means to evaluate decisions/alternatives within the model. The objective was to assist the decision maker in solving a problem or set of problems. The site under study has a groundwater contamination problem, as a result of waste burial practices from the late 50's to the late 70's that pose a potential threat to the environment as well as to health. Problem definition was to choose the best alternative that minimized both the cost of remediation and environmental risk.

Tool Utilized and Methodology Applied

The Decision Analysis TreeAge™ (DATA™) software package was used to model the decision making process. DATA™ was designed to apply the techniques of decision analysis in an intuitive and easy-to-use manner by transforming the potentially complex decision making processes into an easily applied and very visual output (DATA™, 1994). DATA™ permits users to edit large trees quickly, thereby making it desirable to decision makers, who often need to make adjustments to ongoing decision trees without having to start the entire process afresh.

The initial step in developing a decision tree was to scope the problem at hand and develop a flow diagram depicting all the necessary steps to be taken. This process is tedious and usually requires changes or adjustments to the tree (Wang, 2001). The remedial plan design for this study was evaluated from three perspectives with respect to the manner of waste handling and disposal. Namely:

1. Remediation planning based on chemical waste remediation, handling and disposal,
2. Remediation planning based on radioactive waste remediation, handling and disposal,
3. Remediation planning based on mixed waste remediation, handling and disposal.

Figures 3-7 and 3-8 represent collapsed decision trees developed for the scenarios mentioned above. Figure 3-7 was the format developed for chemical wastes handling and disposal, whereas Figure 3-8 is a format of the decision tree developed for remediation planning based on either radioactive waste or mixed waste. The difference between both trees lies in the structure of the “Remediation Action” branch. Figure 3-7 does not contain the “Soil Washing/Treatment” (technology only recommended for soils contaminated with low-level radioactive materials) option whereas in Figure 3-8, each of the 100%, 50% and 25% remediation options are further spilt into “Excavation” and “Soil

Washing”. The contents and structure of decision trees are described in more details below.

With reference to both Figures 3-7 and 3-8, the first hypothetical decision confronted by the decision maker was to either perform or for-go “Additional Testing”. Due to the limitation of the page size, the “No Additional Testing” branch was collapsed in both Figures 3-7 and 3-8, but the sub-trees emanating from it are identical to that following the “Additional Testing” node.

After a decision has been made in favor of/or against additional testing, the next decisions of “Remedial Action” or “No Remedial Action” follows. If “Remedial Action” was selected, then the choice of which remediation technology to be applied must be made. In Figure 3-7 (chemical waste remediation), four (4) options were available to the planners: 100%, 50% or 25% excavation of the management area, and capping and slurry wall installation around the management area. Whereas in Figure 3-8 (radioactive or mixed waste remediation), five (5) alternatives were available to the planners: 100%, 50% or 25% excavation of the management area, capping and slurry wall installation around the management area, and also soil treatment/washing was including in this option. If the planners chose to go with the “No Action” alternative, then the option of a “Monitored Natural Attenuation” was automatically selected.

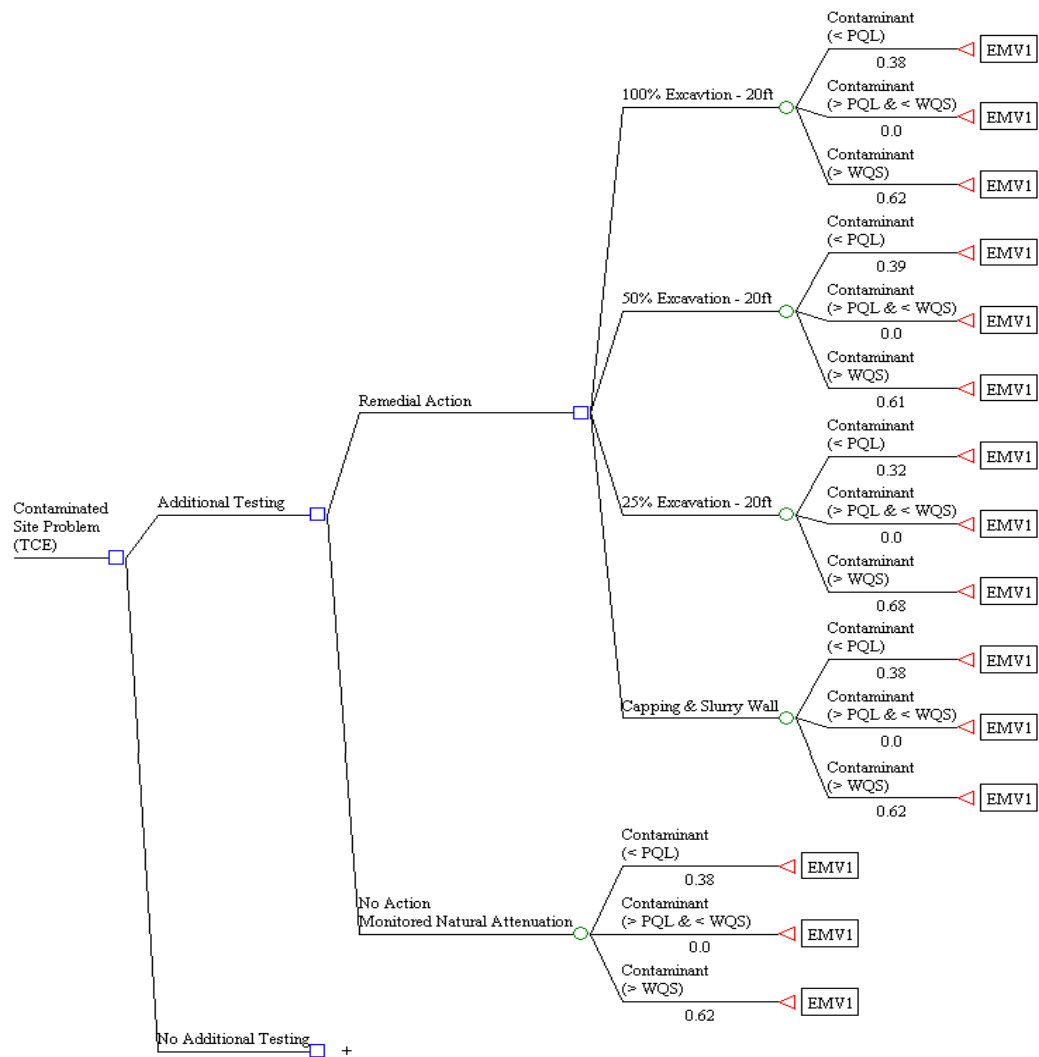


Figure 3-7. Collapsed decision tree based on chemical waste remediation, handling and disposal, showing vital nodes within tree

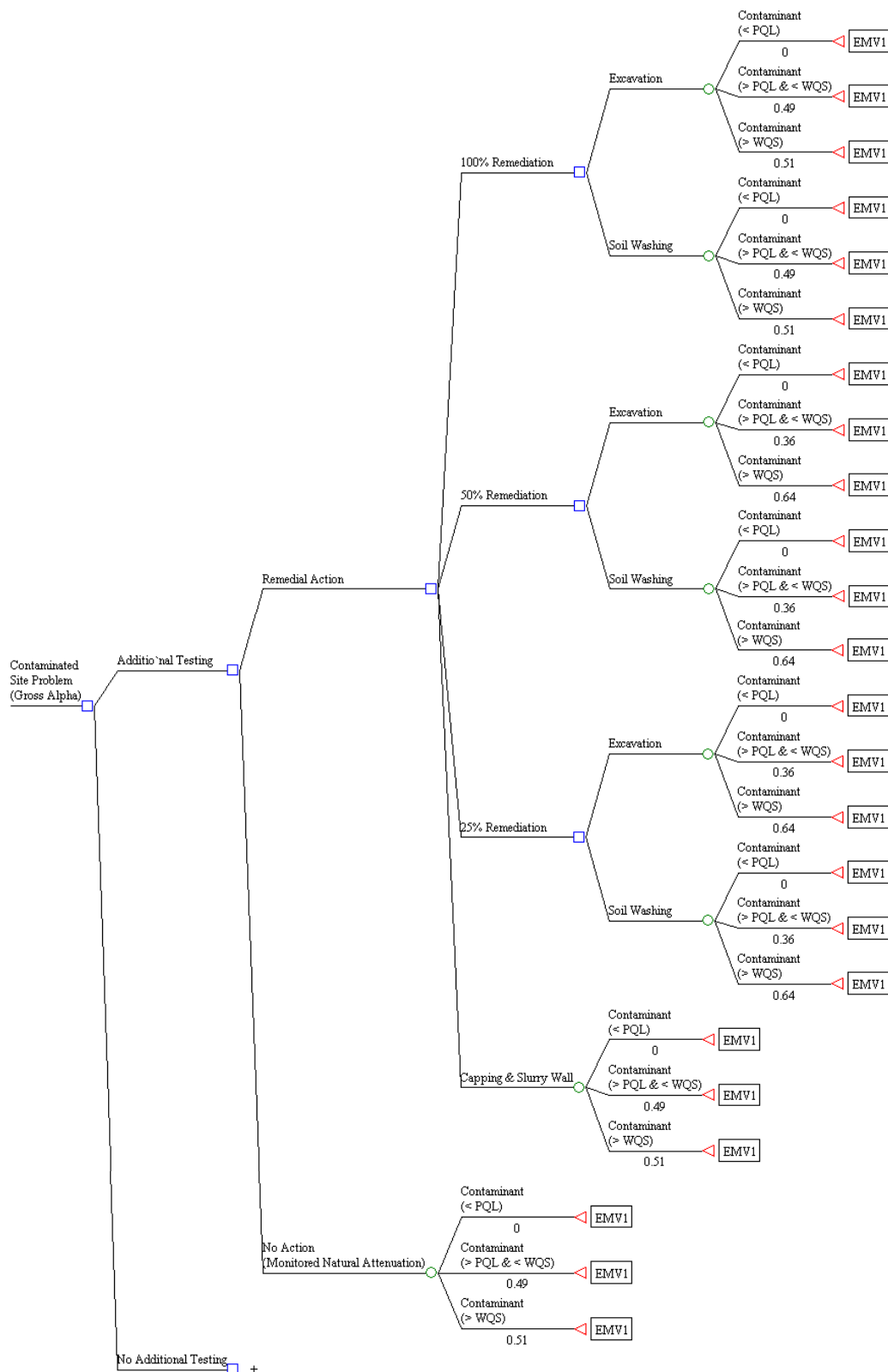


Figure 3-8. Collapsed decision tree based on either radioactive waste or mixed waste remediation, handling and disposal, showing vital nodes within tree

The branches preceding the end (triangular) nodes have the three previously defined states of nature written above them as: Contaminant ($< \text{PQL}$), Contaminant ($\text{PQL} < \text{WQS}$), and Contaminant ($> \text{WQS}$) with the estimated probability of occurrence of each written directly below it. Based on these, DATATM calculates the EMV values of each decision path and presents it as output in the rectangular boxes labeled EMV1 (Figures 3-6 and 3-7). Users can specify in DATATM if the preferred EMV is the minimum or the maximum. For this work, the minimum EMV was selected as the preferred value, since the aim of the exercise was to minimize cost.

In Chapter IV of this report, the results of the decision trees are presented and discussed in more details.

CHAPTER IV

RESULTS

The preceding chapter presented the methodologies adopted during this decision analysis. In this section of the report, the results from the calculations and analysis mentioned in Chapter III are detailed in the following order:

1. Probabilities of states of nature
2. Objective functions as estimated with RACER
3. Decision tree analysis. This chapter also contains the optimum remediation options determined from the developed models.

Probabilities of States of Nature

The purpose of this analysis was to:

- a. Classify the observed concentrations of the contaminants of concern CoCs into the previously defined states of nature ($P(X)$):
 - i. $P(X_1) = \text{Contaminant concentration} < \text{Practical quantification limit (PQL)}$,
 - ii. $P(X_2) = \text{Contaminant concentration} > \text{PQL and} < \text{Water quality standard (WQS)}$, and
 - iii. $P(X_3) = \text{Contaminant concentration} > \text{WQS}$.

- b. Create a state of nature map for each CoC in gridded format, showing their distribution over the entire 100% of the management area, highlighting areas covered by each state of nature.
- c. Estimating the probability of occurrence of each state of nature as identified from the maps.
- d. Repeating steps 'a' through 'c' for 50% and 25% of the management area to estimate the probability of occurrence of the states of nature based on these percentages.

The distribution contours of each CoC (Figures 3-1 to 3-3) were overlaid by the management area perimeter and printed on gridded papers as shown in Figure 4-1 to 4-3 below. The gridded background of the maps enhanced the process of creating states of nature raster maps of the management area based on inverse weight distance (IDW) principles. IDW is a simple spatial deterministic procedure used to approximate the attribute value of an un-sampled point by weighting the average of known values within the neighborhood, and the weights are inversely related to the distances between the prediction location and the sampled locations (Lu, 2008).

Reclassification of CoC distribution maps (Figures 3-1 to 3-3) into states of nature maps was achieved by grouping the CoC concentrations into the appropriate states of nature range. Each state of nature group area is represented with a distinct color as shown in Figures 4-1 to 4-3. Table 4-1 below illustrates the concentration classes of each CoC and the corresponding state of nature within which each occurs.

Table 4-1: Range of CoC concentrations used to reclassify states of nature of CoCs

CoC Name	P(X ₁)	P(X ₂)	P(X ₃)
TCE (mg/L)	0.0 – 0.005	Ø	> 0.005
EDB (mg/L)	0.0 – 0.005	0.005 – 0.05	> 0.05
Chromium (mg/L)	0.0 – 0.01	0.01 – 0.1	> 0.1
Gross Alpha (PCi/L)	0.0 – 1.26	1.26 – 15	> 15

From Table 4-1 above, notice that, for TCE, there is no concentration range set as the second state of nature (i.e. $P(X_2) = \emptyset$). This is because, for TCE, the practical quantifiable limit (PQL) and the water quality standard (WQS) are the same. That is why there are only two classifications for TCE: 0.0 - 0.005mg/L and > 0.005mg/L for the first ($P(X_1)$) and third ($P(X_3)$) state of nature, respectively. Apart from TCE, the state of nature grouping for EDB and chromium are distinct and listed in Table 4-1. EDB has an initial state of nature ($P(X_1)$) range from 0.0 to 0.005mg/L; the second state of nature ($P(X_2)$) ranges from 0.005 – 0.05mg/L, and any concentration greater than 0.05mg/L falls under the final state of nature ($P(X_3)$). For chromium, the initial state of nature ($P(X_1)$) ranges from 0.0 to 0.01mg/L; the second state of nature ($P(X_2)$) from 0.01 – 0.1mg/L, and the final state of nature ($P(X_3)$) is any concentration greater than 0.1mg/L. Finally, the radioactive material, gross alpha, has an initial state of nature ($P(X_1)$) from 0.0 to 1.26 PCi/L; the second state of nature ($P(X_2)$) from 1.26 – 15 PCi/L, and region that measures a concentration over 15 PCi/L falls into the category of the final state of nature - $P(X_3)$.

Estimating Probability of Occurrence Based on 100% of Management Area

Mapping the above data on gridded paper generated the states of nature maps shown in Figures 4-1, 4-2 and 4-3, representing TCE, EDB and chromium respectively. Different colors (on a colored display) or varying shades of grey (in a black and white display) are used to differentiate one set of grids from the other.

TCE

In Figure 4-1, the management area (chemical and radioactive waste areas, excluding the control area) is outlined in pink. The red (darker) grids within the management area indicate locations with TCE concentration between 0.0 to 0.005mg/L (i.e. first state of nature, $P(X_1)$) and the un-shaded (lighter grids) areas within the management area represent areas where TCE concentrations were detected to be higher than 0.005mg/L (i.e. third state of nature, $P(X_3)$). In summary, based on this analysis,

- Probability of occurrence of the first state of nature (0.0 to 0.005mg/L), $P(X_1) = 0.38$ (or 38% of management area),
- Probability of occurrence of the second state of nature, $P(X_2) = 0$. Because there is no defined range of concentrations
- Probability of occurrence of the third state of nature (> 0.005 mg/L), $P(X_3) = 0.62$ (or 62% of management).

These results are presented in a tabular manner in Table 4-2.

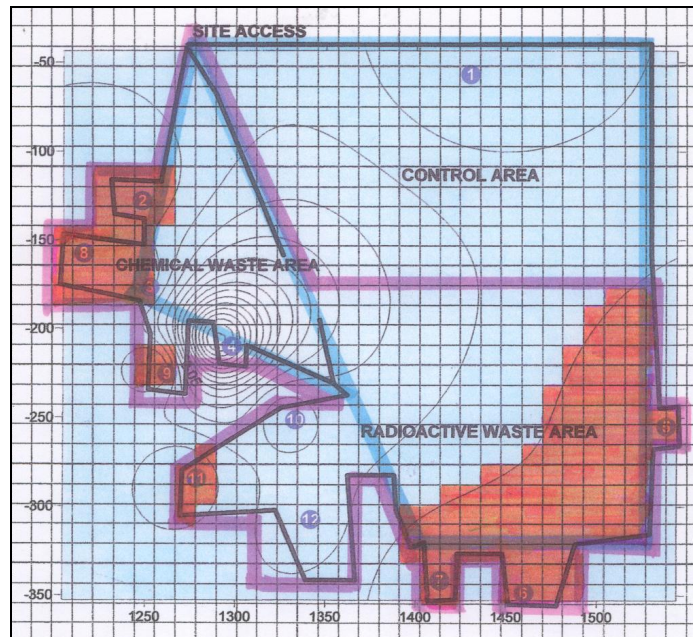


Figure 4-1: TCE state of nature distribution map considering 100% of management area (each grid = 0.004Ac)

EDB

In Figure 4-2, the management area outline is unchanged, the blue-color grids (shaded area around wells 2, 3, 2, 6, 7, 8, 9, 11, 12) represents areas with EDB concentration between 0.0 to 0.005mg/L (i.e. first state of nature, $P(X_1)$), the pink grids (shaded area around well 10) represent the locations with EDB concentrations falling within the range of the second state of nature (0.005 to 0.05mg/L). All other un-shaded grids (yellow background) within the management area represent areas with concentrations higher than 0.05mg/L (i.e. third state of nature, $P(X_3)$). In summary, based on this analysis,

- probability of occurrence of the first state of nature (0.0 to 0.005mg/L), $P(X_1) = 0.38$ (or 38% of management area)
- Probability of occurrence of second state of nature (0.005 to 0.05mg/L), $P(X_2) = 0.03$ (or 3% of the management area); and
- Probability of occurrence of the third state of nature (> 0.005 mg/L), $P(X_3) = 0.59$ (or 59% of management area).

These results are summarized in a tabular manner in Table 4-2.

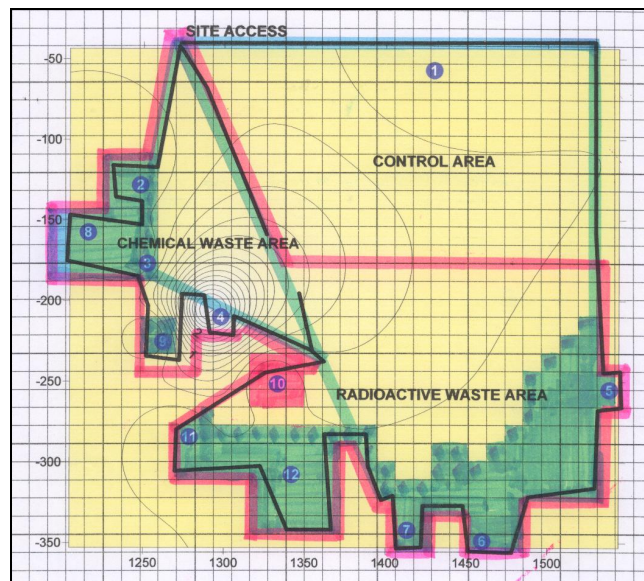


Figure 4-2: EDB state of nature distribution map considering 100% of management area (each grid = 0.004Ac)

Chromium

Figure 4-3 presents a similar map for chromium. As before, the management area comprises entire site excluding the control area. The blue colored (darkest shade) grids within the management area represent areas with chromium concentration ranging from 0.0 to 0.01mg/L (i.e. first state of nature, $P(X_1)$), the pink (lightest shade) background of the diagram depicts areas with concentrations within 0.01 to 0.1mg/L (second state of nature, $P(X_2)$). Finally, the yellow-colored (medium shade) area represents areas with concentrations higher than 0.1mg/L (i.e. third state of nature, $P(X_3)$).

In summary, for chromium,

- Probability of occurrence of the first state of nature (0.0 to 0.01mg/L), $P(X_1) = 0.48$ (or 48% of management area),
- Probability of occurrence of the second state of nature (0.01 to 0.1mg/L), $P(X_2) = 0.39$ (or 39% of management area); and
- Probability of occurrence of the third state of nature (> 0.1 mg/L), $P(X_3) = 0.13$ (or 13% of management area).

These results are tabulated in Table 4-2.

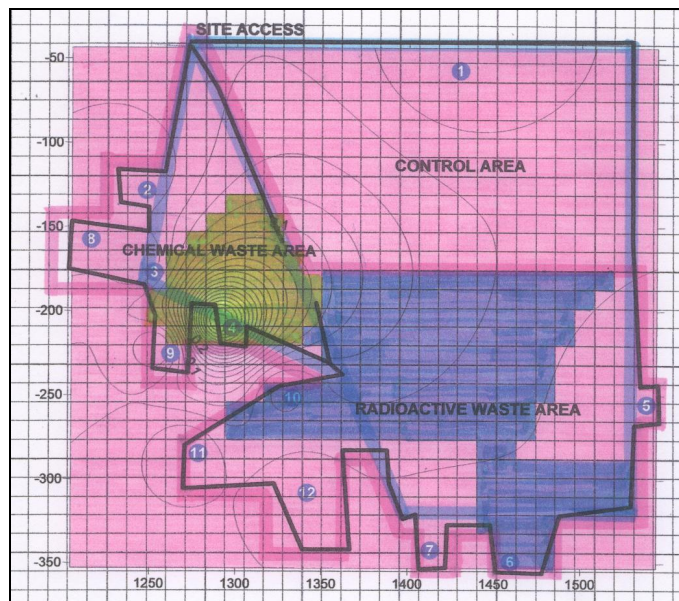


Figure 4-3: Chromium state of nature distribution map considering 100% of management area (each grid = 0.004Ac)

Gross Alpha

This radioactive material was detected in all the existing monitoring wells in the study area (Table 3-1) at concentrations higher than the practical quantifiable level (PQL) of 1.26PCi/L. Therefore the probability of the first state of nature occurring was eliminated. Figure 4-4 shows a gross alpha distribution map, highlighting areas within the management areas with concentration levels falling into the second and third states of nature in blue (darker shade) and orange (lighter shade) respectively. In summary, for gross alpha,

- Probability of occurrence of the first state of nature (0.0 to 1.26 PCi/L), $P(X_1) = 0$
- Probability of occurrence of the second state of nature (1.26 to 15 PCi/L), $P(X_2) = 0.49$ (or 49% of management area)
- Probability of occurrence of the first state of nature (> 15 PCi/L), $P(X_3) = 0.51$ (or 51% of management area)

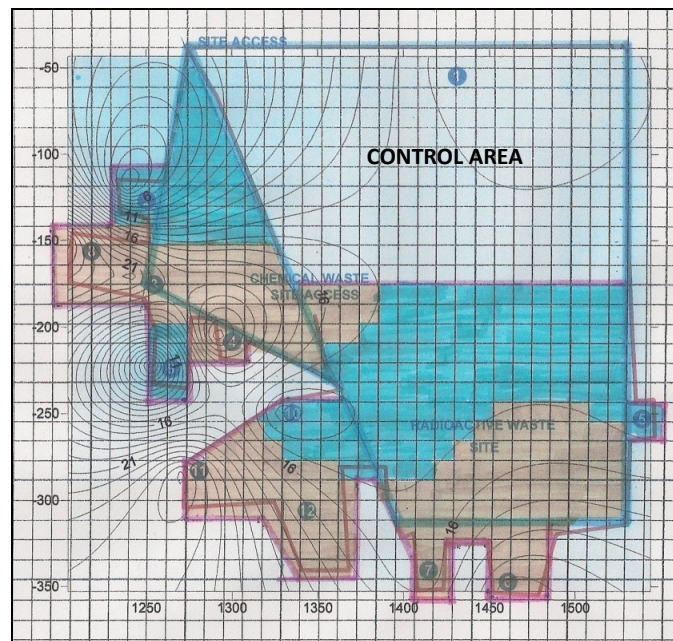


Figure 4-4: Gross Alpha state of nature map considering 100% of the management area (each grid = 0.04Ac)

Table 4-2: Probabilities of states of nature and area occupied by each range of concentration considering 100% of the management area

CoC Name	P(X ₁)		P(X ₂)		P(X ₃)	
	Probability	Area (Ac)	Probability	Area (Ac)	Probability	Area (Ac)
TCE (mg/L)	0.38	0.51	0.00	0.00	0.62	0.84
EDB (mg/L)	0.38	0.51	0.03	0.04	0.59	0.80
Chromium (mg/L)	0.48	0.65	0.39	0.53	0.13	0.18
Gross Alpha	0.00	0.00	0.49	0.66	0.51	0.69

Table 4-2 is structured such that for each CoC, there are three possible state of nature outcomes – P(X₁), P(X₂) and P(X₃). Under each possible outcome are two columns: the first contains the probabilities of occurrence and the second contains the portion of the management area (in Acres) covered by that state of nature. For example, for TCE, the probability of the first state of nature, P(X₁) is 0.38 and the area under this probability is 0.51Ac.

Estimating Probability of Occurrence Based on 50% of Management Area

Remapping the data in Table 4-1 on grid paper, and demarcating 50% of the management area for evaluation by giving priority to locations where higher concentrations of CoCs were indicated, Figures 4-5, 4-6 and 4-7 were generated to depict states of nature maps for TCE, EDB and chromium respectively. Grids considered as 50% management area are clearly identified with different colors.

As with the 100% evaluation (Figures 4-1 to 4-4), estimation of the probability of occurrence was achieved by grouping grids that represent the various ranges of CoC concentration. Unlike in the 100% evaluation, where areas within the same state of nature were demarcated with distinct color combinations, here, one color (if in color) or darker shade (if in black and white), was used to demarcate the 50% portion of the management area considered for this analysis (Figures 4-5, 4-6, and 4-7). Finally, grids within the

same concentration range were grouped, as before, to estimate the probabilities of state of nature. The outcomes of these analyses are presented below.

TCE

In Figure 4-5, the outline of the management area is the entire site area excluding the control area and 50% of the management areas indicating the highest concentration of TCE are colored pink (darker shades). Based on 50% evaluation of the management area,

- Probability of occurrence of the first state of nature (0.0 to 0.005 mg/L), $P(X_1) = 0.39$ (or 19.5% of the management area)
- Probability of occurrence of the second state of nature, $P(X_2) = 0$. Because there is no defined range of concentrations
- Probability of occurrence of the third state of nature (> 0.005 mg/L), $P(X_3) = 0.61$ (or 30.5% of the management area)

These results are summarized in a tabular form in Table 4-3.

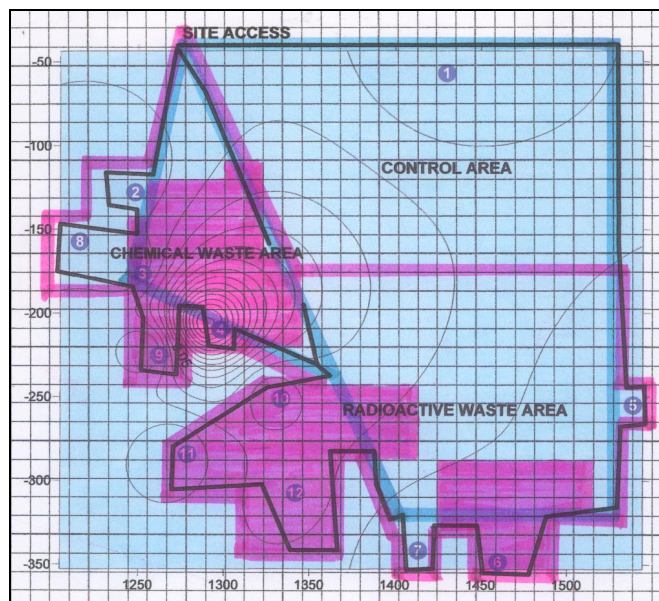


Figure 4-5: TCE state of nature distribution map considering 50% of management area (each grid = 0.004 ac)

EDB

In Figure 4-6, the management area is the entire site area excluding the control area and 50% of the management areas indicating the highest concentration of EDB are the green colored (or darker shades) grids.

- Probability of occurrence of the first state of nature (0.0 to 0.005 mg/L), $P(X_1) = 0.51$ (or 25.5% of the management area)
- Probability of occurrence of the second state of nature (0.005 to 0.05 mg/L), $P(X_2) = 0.03$ (or 1.5% of management area), and
- Probability of occurrence of the third state of nature (> 0.05 mg/L), $P(X_3) = 0.46$ (or 23% of the management area).

These results are presented in a tabular manner in Table 4-3.

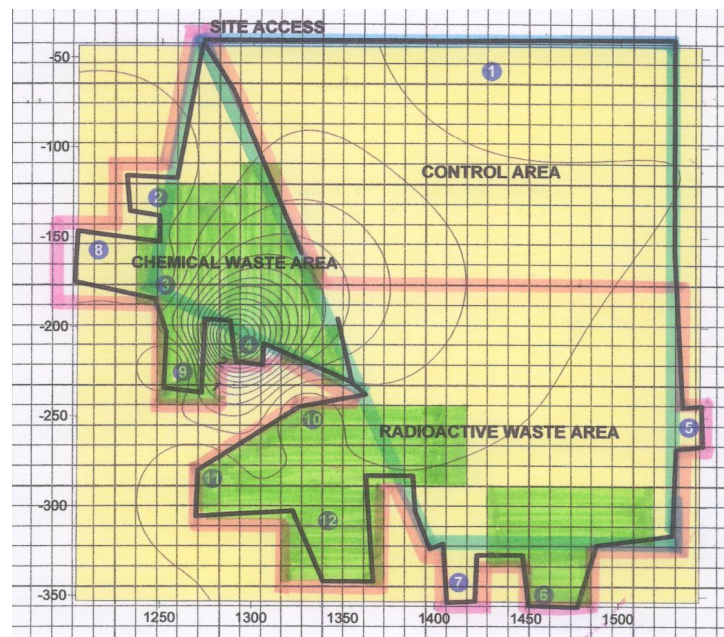


Figure 4-6: EDB state of nature distribution map showing 50% of management area considered for analysis (each grid = 0.004 ac)

Chromium

In Figure 4-7, the management area is the entire site area excluding the control area and 50% of the management areas indicating the highest concentration of chromium are the green colored grids.

- Probability of occurrence of the first state of nature (0.0 to 0.01 mg/L), $P(X_1) = 0.41$ (or 20.5% of the management area)
- Probability of occurrence of the second state of nature (0.01 to 0.1 mg/L), $P(X_2) = 0.38$ (or 19% of the management area), and
- Probability of occurrence of the third state of nature (> 0.1 mg/L), $P(X_3) = 0.21$ (or 10.5% of the management area).

These results are presented in a tabular manner in Table 4-3.

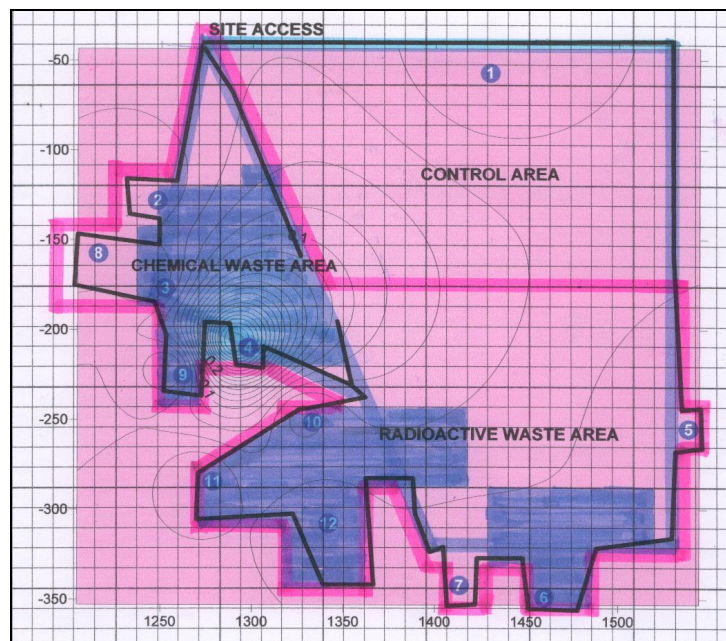


Figure 4-7: Chromium state of nature distribution map showing 50% of management area considered for analysis (each grid = 0.004 ac)

Gross Alpha

50% analysis of this CoC was achieved by performing a simple proportion of the number of wells with detected concentration within a given state of nature range, divided by the total wells with respect to half of the management area. For example, concentration of gross alpha detected in four wells (MW 3, 7, 8 and 11) fell into the second state of nature (i.e. concentration exceeded the PQL, but was less than the WQS).

Therefore: Number of wells = 4,

Total number of wells = 11,

Area of 50% management area = 0.675 acres.

So: $P(X_2) = 4/11 * 100\% = 36\%$ (or 18% of management area, or 0.243 ac).

In summary, for gross alpha:

- Probability of occurrence of the first state of nature (0.0 to 1.26 pCi/L), $P(X_1) = 0$
- Probability of occurrence of the second state of nature (1.26 to 15 pCi/L), $P(X_2) = 0.36$ (or 18% of management area)
- Probability of occurrence of the first state of nature (> 15 pCi/L), $P(X_3) = 0.64$ (or 32% of management area)

These results are summarized in Table 4-3 below.

Table 4-3: Probabilities of states of nature and area occupied by each range of concentration considering 50% of the management area

CoC Name	P(X ₁)		P(X ₂)		P(X ₃)	
	Probability	Area (ac)	Probability	Area (ac)	Probability	Area (ac)
TCE (mg/L)	0.39	0.26	0.00	0.00	0.61	0.41
EDB (mg/L)	0.51	0.34	0.03	0.02	0.46	0.31
Chromium (mg/L)	0.41	0.28	0.38	0.26	0.21	0.14
Gross Alpha	0.00	0.00	0.36	0.25	0.64	0.43

Table 4-3 is structured such that for each CoC, there are three possible state of nature out comes – $P(X_1)$, $P(X_2)$ and $P(X_3)$. Under each possible outcome are two columns: the first contains the probabilities of occurrence and the second contains the portion of the management area (in Acres) covered by that state of nature. For example, for TCE, the probability of the first state of nature, $P(X_1)$ is 0.39 and the area under this probability is 0.26 ac. Also, the areas estimated in this table are with reference to the 50% entire management area. For example, Area occupied by TCE – $P(X_1) = 0.39 * 1.35 * 0.5 = 0.26$ ac.

Estimating Probability of Occurrence Based on 25% of management Area

Remapping the data in Table 4-1 on grid paper, and demarcating 25% of the management area for evaluation by giving priority to locations indicating highest concentrations of CoC, Figures 4-8, 4-9 and 4-10 were generated to illustrate the states of nature maps for TCE, EDB and chromium, respectively. As with the 50% evaluation, one color (if in color) or darker shade (if in black and white) was used to demarcate the 25% portion of the management area considered for this analysis (Figures 4-8, 4-9, and 4-10), and then applicable grids were carefully grouped to estimate the probabilities of occurrence. The outcomes of these analyses are presented below.

TCE

In Figure 4-8, the management area includes the entire site area excluding the control area and 25% of the management areas indicating the highest concentration of TCE are also colored with pink (darker shade).

Based on 25% evaluation of the management area,

- Probability of occurrence of the first state of nature (0.0 to 0.005 mg/L), $P(X_1) =$

0.32 (or 8% of the management area)

- Probability of occurrence of the second state of nature, $P(X_2) = 0$. Because there is no defined range of concentrations
- Probability of occurrence of the third state of nature (> 0.005 mg/L), $P(X_3) = 0.68$ (or 17% of the management area)

These results are summarized in a tabular form in Table 4-4

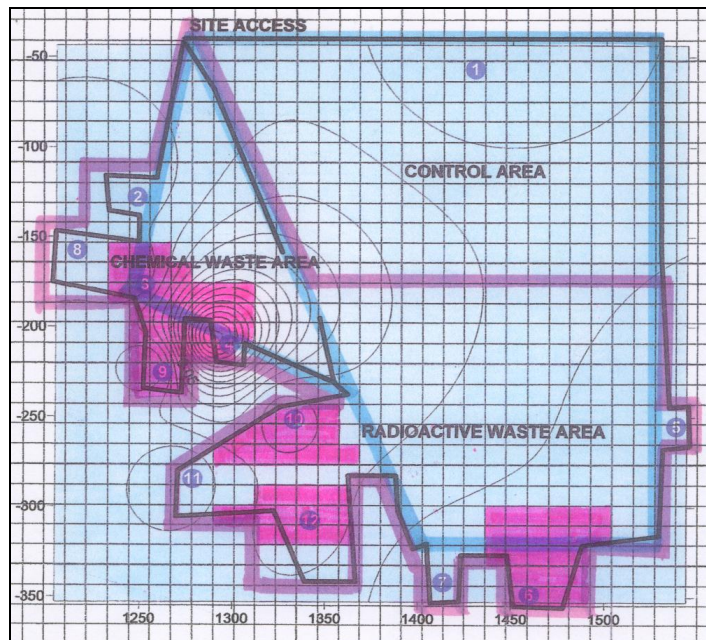


Figure 4-8: TCE state of nature distribution map considering 25% of management area (each grid = 0.004 ac)

EDB

In Figure 4-9, the management area is outlined with the pink line and 25% of the management areas indicating the highest concentration of EDB are the green colored (darker shade) grids.

- Probability of occurrence of the first state of nature (0.0 to 0.005 mg/L), $P(X_1) = 0.57$ (or 14.25% of the management area)

- Probability of occurrence of the second state of nature (0.005 to 0.05 mg/L), $P(X_2) = 0.08$ (or 2% of management area), and
- Probability of occurrence of the third state of nature (> 0.05 mg/L), $P(X_3) = 0.35$ (or 8.75% of the management area).

These results are presented in a tabular manner in Table 4-4.

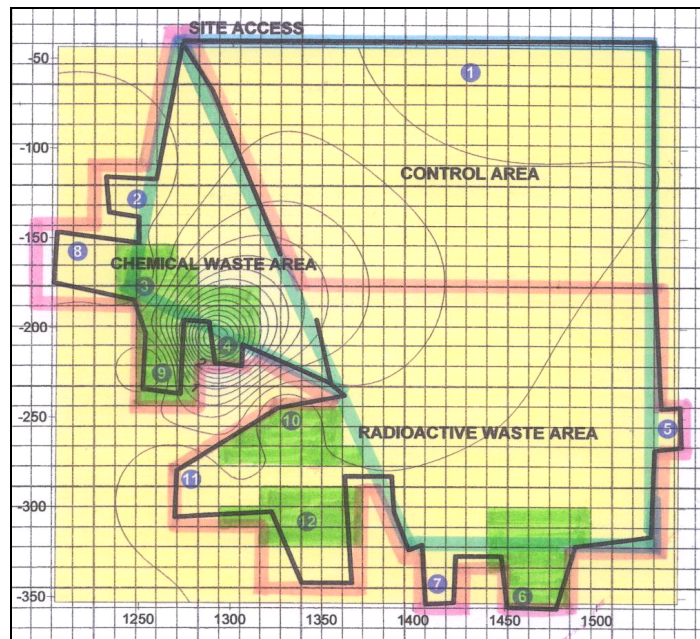


Figure 4-9: EDB state of nature distribution map considering 25% of management area (each grid = 0.004 ac)

Chromium

In Figure 4-10 below, the management area is outlined with the pink line and 25% of the management areas indicating the highest concentration of chromium are the blue colored (darker shade) grids.

- Probability of occurrence of the first state of nature (0.0 to 0.01 mg/L), $P(X_1) = 0.33$ (or 8.25% of the management area)
- Probability of occurrence of the second state of nature (0.01 to 0.1 mg/L), $P(X_2) =$

0.50 (or 12.5% of the management area), and

- Probability of occurrence of the third state of nature (> 0.1 mg/L), $P(X_3) = 0.17$ (or 4.25% of the management area).

These results are presented in a tabular manner in Table 4-4.

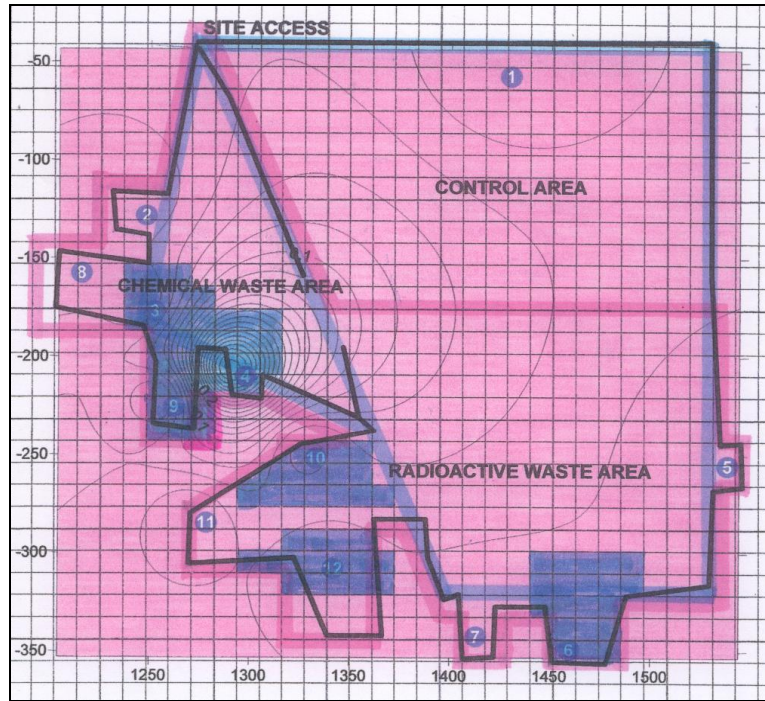


Figure 4-10: Chromium state of nature distribution map considering 100% of management area (each grid = 0.004 ac)

Gross Alpha

25% analysis of this CoC was achieved by performing a simple proportion of the number of wells with detected concentration within a given state of nature range, divided by the total wells with respect to half of the management area. For example, concentration of gross alpha detected in four wells (MW 3, 7, 8 and 11) fell into the second state of nature (i.e. concentration exceeded the PQL, but was less than the WQS).

Therefore: Number of wells = 4,

Total number of wells = 11,

Area of 25% management area = 0.3375 acres.

So: $P(X_2) = 4/11 * 100\% = 36\%$ (or 12% of management area, or 0.164 ac).

In summary, for gross alpha:

- Probability of occurrence of the first state of nature (0.0 to 1.26 pCi/L), $P(X_1) = 0$
- Probability of occurrence of the second state of nature (1.26 to 15 pCi/L), $P(X_2) = 0.36$ (or 12% of management area)
- Probability of occurrence of the first state of nature (> 15 pCi/L), $P(X_3) = 0.64$ (or 16% of management area)

These results are summarized in Table 4-4.

Table 4-4: Probabilities of states of nature and area occupied by each range of concentration considering 25% of the management area

CoC Name	P(X ₁)		P(X ₂)		P(X ₃)	
	Probability	Area (Ac)	Probability	Area (Ac)	Probability	Area (Ac)
TCE (mg/L)	0.32	0.11	0.00	0.00	0.68	0.23
EDB (mg/L)	0.57	0.19	0.08	0.03	0.35	0.12
Chromium (mg/L)	0.33	0.11	0.50	0.17	0.17	0.06
Gross Alpha	0.00	0.00	0.36	0.12	0.64	0.22

Remediation Cost Analysis/Objective Functions Estimation
Costing the four remediation techniques mentioned in preceding chapters

(excavation, soil treatment/washing, capping and slurry wall installation and monitored natural attenuation) considered for cleaning up the OSU's burial site was done with RACER™ (Remedial Action Cost Estimation Requirement™). This section presents the estimation criteria and estimated cost of each option.

Excavation

As mentioned earlier, three excavation scenarios were calculated for with RACER™ – 100%, 50% and 25% - based on two excavation options – 20 ft excavation and 30 ft excavation of the management area. For the 20 ft excavation option, it was assumed that the top 10 ft of excavated materials were uncontaminated and would be reused as backfill and that additional backfill would be sourced from around the site. The bottom 10 ft, assumed to be the depth of contamination, would be transported to an appropriate landfill for disposal. For this analysis, a landfill with an operating license to handle both single wastes and mixed wastes, operated by Energy Solution in Utah was selected as the disposal location.

Tables 4-5 to 4-8 enumerate the cost of each component for all the excavation scenarios (i.e. 100%, 50% and 25%). The last and penultimate columns in the table titled: “Mixed Waste RACER™ Estimate (USD)” and “Single Waste RACER™ Estimate (USD)”, respectively, contain the cost of treating the waste as either a mixed waste site or as a single (chemical or radioactive waste site). A common trend observed when comparing the cost of mixed waste handling to the cost of handling single waste reveals considerably higher cost for the former.

The 30 ft excavation costing alternatives were also included to avail site managers

with more alternatives to select from and to define a “worst” case scenario which could occur if waste migration had occurred. Here, up to 30 ft would be excavated and the entire waste transported and disposed at the same landfill mentioned above. In addition, 30 ft of uncontaminated backfill would also be imported from nearby sites. Table 4-6 enumerates the cost of each component for all the excavation scenarios – 100%, 50% and 25%.

Table 4-5: 20 ft Excavation: cost components and RACER™ estimates

Excavation Option	Component	Single Waste RACER™ Estimate (USD)	Mixed Waste RACER™ Estimate (USD)
100%	Remediation Action Cost, C(t)	4,126,949.00	10,602,717.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	355,299.00	355,299.00
	Post-remediation Monitoring Cost, M(t)	1,214,579.00	1,214,579.00
50%	Remediation Action Cost, C(t)	2,077,045.00	5,314,929.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	178,893.00	178,893.00
	Post-remediation Monitoring Cost, M(t)	659,254.00	659,254.00
25%	Remediation Action Cost, C(t)	1,048,282.00	2,667,224.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	97,815.00	97,815.00
	Post-remediation Monitoring Cost, M(t)	373,425.00	373,425.00

Close scrutiny of the cost of each excavation alternative in Tables 4-5 (above) and 4-6 (below), reveals that the remediation action cost, additional testing cost, and post-remediation monitoring cost decrease arithmetically by a factor of two (2),

approximately, from 100% to 25% excavation. This is because the amounts of these components are directly proportional to the size of the area to be treated, so, the bigger the area considered, the higher the project costs. On the other hand, the failure cost remained unchanged in all three cases, because as described in Chapter III, the cost of failure of any excavation option was set as the cost of implementing the most extreme remedial plan - remediation and monitoring cost of 30 ft excavation of 100% of the management area based on mixed waste handling.

$$\begin{aligned} \text{i.e.: Failure cost, } R(t) &= \text{Remediation Cost, } C(t)_{30 \text{ ft, Mixed Waste}} + \text{Monitoring Cost, } M(t) \\ &= 31,596,360.00\text{USD} + 1,214,579.00\text{USD} = 32,783,939.00 \text{ USD} \end{aligned}$$

A Comparison of Table 4-5 and Table 4-6 shows that three of the cost components, failure cost, additional testing cost and post-remediation monitoring costs, were the same for all corresponding scenarios. The estimated remediation costs were approximately three times more in Table 4-6 than they were for corresponding options in Table 4-5. The higher cost observed was expected because the 30 ft excavation alternative was expected to involve more waste handling and disposal than the 20 ft alternative. It would be expected that the cost components for the 30 ft alternative would be one-and-half times more than those of the 20ft alternative, but that was not the case, rather, a factor difference of three was observed. The reason for this disparity was because, as mentioned at the beginning of this section, only 10 ft of material would be disposed on in the 20 ft excavation alternative since the top 10 ft was expected to be reused as back fill.

Table 4-6: 30 ft Excavation: cost components and RACER™ estimates

Excavation Option	Component	Single Waste RACER™ Estimate (USD)	Mixed Waste RACER™ Estimate (USD)
100%	Remediation Action Cost, C(t)	12,169,054.00	31,596,360.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	355,299.00	355,299.00
	Post-remediation Monitoring Cost, M(t)	1,214,579.00	1,214,579.00
50%	Remediation Action Cost, C(t)	6,118,901.00	15,832,554.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	178,893.00	178,893.00
	Post-remediation Monitoring Cost, M(t)	659,254.00	659,254.00
25%	Remediation Action Cost, C(t)	3,083,337.00	7,940,164.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	97,815.00	97,815.00
	Post-remediation Monitoring Cost, M(t)	373,425.00	373,425.00

Soil Treatment/Washing

Also considered for remediation was a technology developed for treating soils contaminated with low level radioactive substances (RACER™, 2008; FRTR, Mar. 2010). This process typically involves excavation of contaminated soil, washing the soil with specific surfactants to concentrate the contaminants in the finer fraction of the feed soil, and disposing of the fines (RACER™, 2008). It is a volume reduction process that requires disposal of only a portion of the excavated material, thereby reducing the amount of waste to be disposed and the amount of additional backfill required. Based on these, RACER™ was used to estimate the cost of soil treatment after excavating 20 and 30 ft of the management area. Tables 4-7 and 4-8 summarize these estimates.

Table 4-7: 20 ft Soil treatment/washing: cost components and RACER™ estimates

Soil Washing Option	Component	Single Waste RACER™ Estimate (USD)	Mixed Waste RACER™ Estimate (USD)
100%	Remediation Action Cost, C(t)	3,900,538.00	4,742,567.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	355,299.00	355,299.00
	Post-remediation Monitoring Cost, M(t)	1,214,579.00	1,214,579.00
50%	Remediation Action Cost, C(t)	2,258,002.00	2,679,017.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	178,893.00	178,893.00
	Post-remediation Monitoring Cost, M(t)	659,254.00	659,254.00
25%	Remediation Action Cost, C(t)	1,421,611.00	1,632,118.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	97,815.00	97,815.00
	Post-remediation Monitoring Cost, M(t)	373,425.00	373,425.00

The cost estimates in Table 4-7 indicated a similar trend to Tables 4-5 and 4-6: the larger the area selected for treatment, the higher the cost of treatment required. In comparison to Table 4-5 (20 ft excavation estimates), soil washing was found to cost less only if 100% of the site was to be excavated and washed. If not, the remediation cost of excavation of 20 ft of either the 50% or the 25% of the area, without soil washing, were found to cost less. This is because the soil washing technique involves use of surfactants (detergents) for washing contaminated soils, and treatment of waste water generated as a result of this procedure. So, unless there is a significantly large amount of soil to be treated, investing in the soil washing equipments and material may not be the preferred alternative.

Table 4-8: 30 ft Soil treatment: cost components and RACER™ estimates

Excavation Option	Component	Single Waste RACER™ Estimate (USD)	Mixed Waste RACER™ Estimate (USD)
100%	Remediation Action Cost, C(t)	10,302,613.00	12,828,104.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	355,299.00	355,299.00
	Post-remediation Monitoring Cost, M(t)	1,214,579.00	1,214,579.00
50%	Remediation Action Cost, C(t)	5,630,587.00	6,893,630.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	178,893.00	178,893.00
	Post-remediation Monitoring Cost, M(t)	659,254.00	659,254.00
25%	Remediation Action Cost, C(t)	3,076,094.00	3,707,615.00
	Failure Cost, R(t)	32,783,939.00	32,783,939.00
	Additional Testing cost, T(t)	97,815.00	97,815.00
	Post-remediation Monitoring Cost, M(t)	373,425.00	373,425.00

As in Tables 4-5, 4-6 and 4-7, Table 4-8 also showed similar trends when comparing the cost of 100%, 50% and 25% soil treatment, in that the cost of remediation increased as the size of the treatment area also increased. However, in comparison to Table 4-6 (30 ft excavation), it was generally more economical to wash the excavated soil before disposing (with values ranging from a few thousand USD to several million USD). This way, only the fines containing the concentrated contaminated would be disposed rather than disposing the entire 30 ft of excavated contaminated soil.

Capping and Slurry Wall

The cost components and RACER™ estimates associated with capping of the management area and construction of a slurry wall around its perimeter are enumerated in Table 4-9. The monetary requirements were found to be the same regardless of whether remediation design was based on chemical waste treatment or on radioactive waste treatment.

The estimated technology cost requirement of applying this option was found to be significantly cheaper than any of the excavation or soil washing option. For example, the technology cost of capping and slurry wall installation (Table 4-9) when compared to the cost of 100% - 30 ft excavation (Table 4-8), was approximately twenty-four times less costly. Other cost components, however, were not so. The additional testing cost was the same as in the case of 100% excavation or soil washing, because the same treatment area was involved in either case (1.35 acres). The post remediation monitoring cost was three times more for this technology than it was for excavation, because the monitoring period set for capping and slurry wall installation was three times more than was set for excavation (cap and slurry wall – 15 years vs. excavation – 5 years). Finally, the failure cost for capping and slurry wall installation was significantly more than it was for both excavation and soil treatment for the same reason mentioned before – it was projected for a period of 15 years rather than 5 years.

Table 4-9. Capping and slurry wall: cost components and RACER™ estimates

Capping and Slurry Wall	Component	RACER™ Estimate (USD)
	Remediation Action Cost, C(t)	431,694.00
	Failure Cost, R(t)	53,401,582.00
	Additional Testing cost, T(t)	355,299.00
	Post-remediation Monitoring Cost, M(t)	3,103,609.00

Monitored Natural Attenuation

The cost components and RACER™ estimates associated with not applying any remedial technology to the management area, but consistently monitoring the CoC concentration in the soil and groundwater over a period of 25 years are summarized in Table 4-10. As in the case of capping and slurry wall installation, the monetary requirements for a monitored natural attenuation program was also found to be the same regardless of whether remediation design was based on chemical waste treatment or on radioactive waste treatment.

Table 4-10. Monitored natural attenuation: cost components and RACER estimates

Monitored Natural Attenuation	Component	RACER™ Estimate (USD)
	Failure Cost, R(t)	86,985,550.00
	Additional Testing cost, T(t)	355,299.00
	Post-remediation Monitoring Cost, M(t)	4,945,580.00

Since there is no actual remediation activity involved in this option, the remedial action cost was 0.00USD. The cost of additional testing in this case was the same as for 100% excavation because they both involved the whole management area, but the costs of failure and post-remediation monitoring are estimated over a period of 25 years, which is why they are significantly higher than those estimated for all other options. It is also worth mentioning that the failure cost referred to for this alternative is the same as for all other options – 30 ft excavation and disposal of mixed waste.

Decision Model

The results presented under this section are the decision trees developed using DATA™. These trees depict the decision paths based on each CoC, EMVs for each path and a recommended EMV for each tree based on the lowest value.

Format of Trees Presentation

First, there are two groups of trees based on the failure assessment scenarios:

- Scenario 1, i.e. failure check after 5 years, 15 years and 25 years for excavation/soil washing, capping/slurry wall and MNA, respectively: comprised of Figures 4-11 to 4-20
- Scenario 2, i.e. failure check after 1 years, 5 years and 5 years for excavation/soil washing, capping/slurry wall and MNA, respectively: comprised of Figures 4-21 to 4-30

Secondly, trees within each scenario were subdivided according to depth to be excavated into:

1. Alternative 1(20 ft Remediation): Figures 4-11 to 4-15 and Figures 4-21 to 4-25
2. Alternative 2: 30 ft Remediation: Figures 4-16 to 4-20 and Figures 4-26 to 4-30

Finally, trees under each alternative were further subdivided according to waste type into:

- A. Chemical Wastes: Figures 4-11 – 4-13; 4-16 – 4-18; 4-21 – 4-23; 4-26 – 4-28
- B. Radioactive/Mixed wastes: Figures 4-14 & 4-15; 4-19 & 4-20; 4-24 & 4-25; 4-29 & 4-30.

Scenario 1: Failure Assessment after Pre-set Post-Remediation Monitoring Period

Figures 4-11 to 4-20 shown below depict the decision trees, optimum decision paths and optimum EMVs developed based on the assumption that failure or success of the site remediation will be assessed after the pre-set post-remediation monitoring period.

Alternative 1: Design Based on 20 ft Excavation

The decision trees developed under this alternative assume that only 20 ft contaminated soil will be excavated. The top 10 ft of excavated material would be reused for filling,

whereas the bottom 10 ft would either be disposed completely or washed before disposing.

A. Decision Trees for Chemical Waste Handling

Figures 4-11, 4-12 and 4-13 illustrates decision trees that are based on the three chemical CoCs (TCE, EDB and chromium, respectively), under Scenario 1 and with only 20 ft of excavation. With reference to Figure 4-11 (TCE), the optimum decision path is indicated by the darkened nodes. The optimum decision path suggested by this tree was to perform “No Additional Testing” and to take “Remedial Action” by 50% excavation of the management area. The optimum EMV recommended is \$23.53 million USD. Note that the double-hatched (//) lines denote non-optimal paths. Figure 4-12 (EDB) on the other hand suggests a different optimum path: perform “No Additional Testing” and take “Remedial Action” by 25% excavation of the management area. The optimum EMV recommended is \$19.65 million USD. Figure 4-13 (chromium) suggests a similar path as Figure 4-11: No Additional Testing”, take “Remedial Action” by 50% excavation of the management area, with a calculated optimum EMV of \$15.90 million USD.

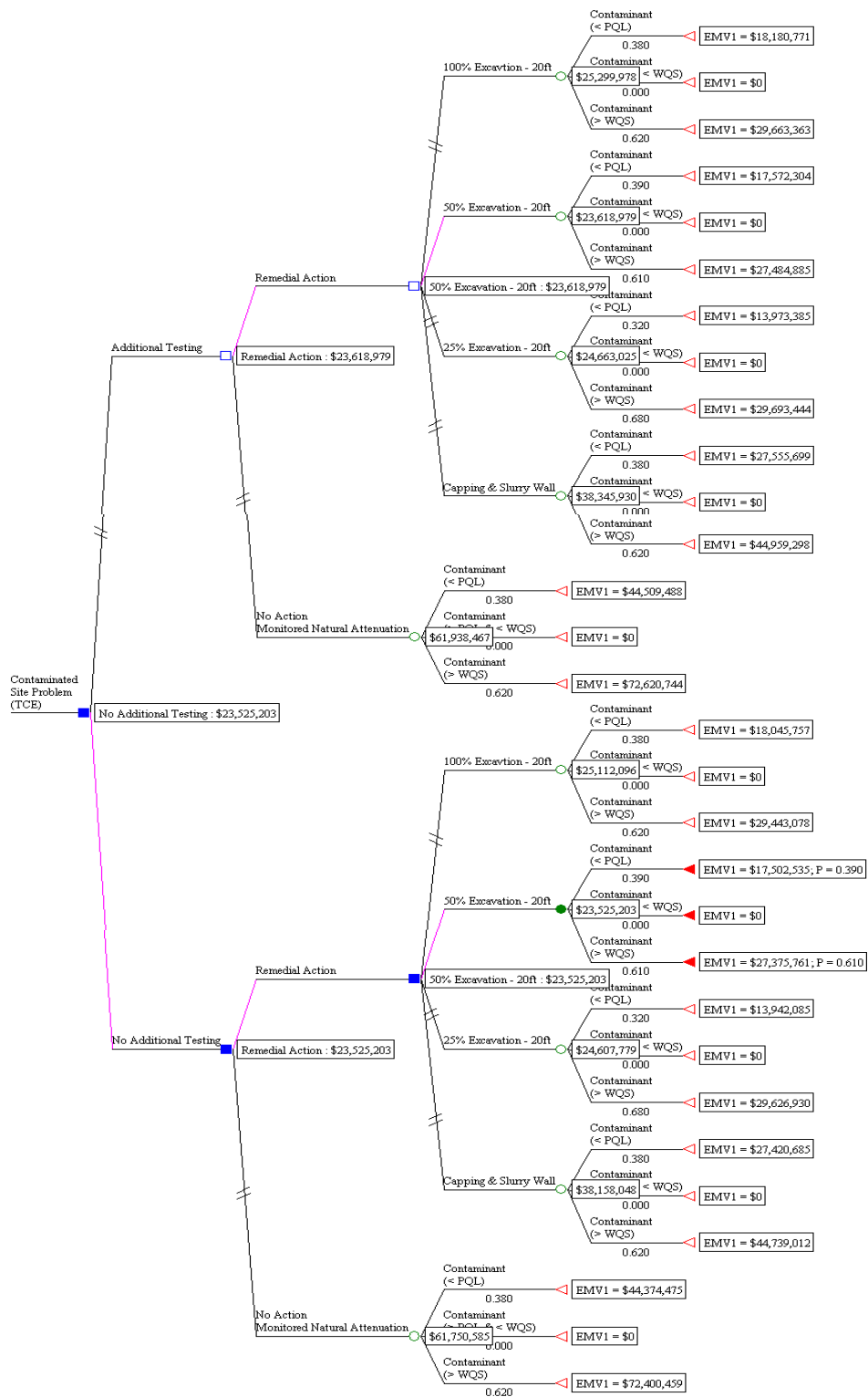


Figure 4-11: Decision tree for TCE based on 20 ft excavation under Scenario 1

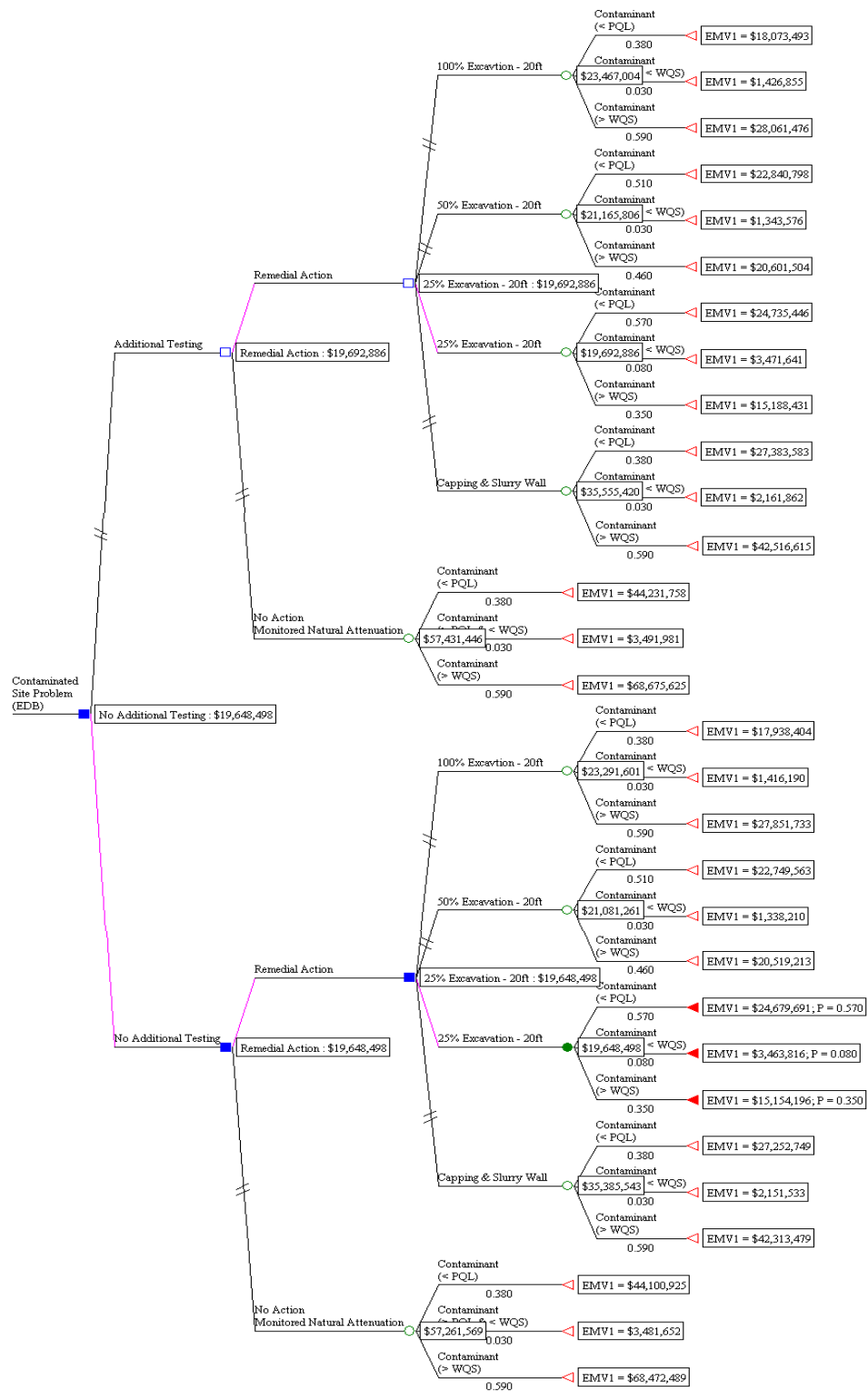


Figure 4-12: Decision tree for EDB based on 20 ft excavation under Scenario 1

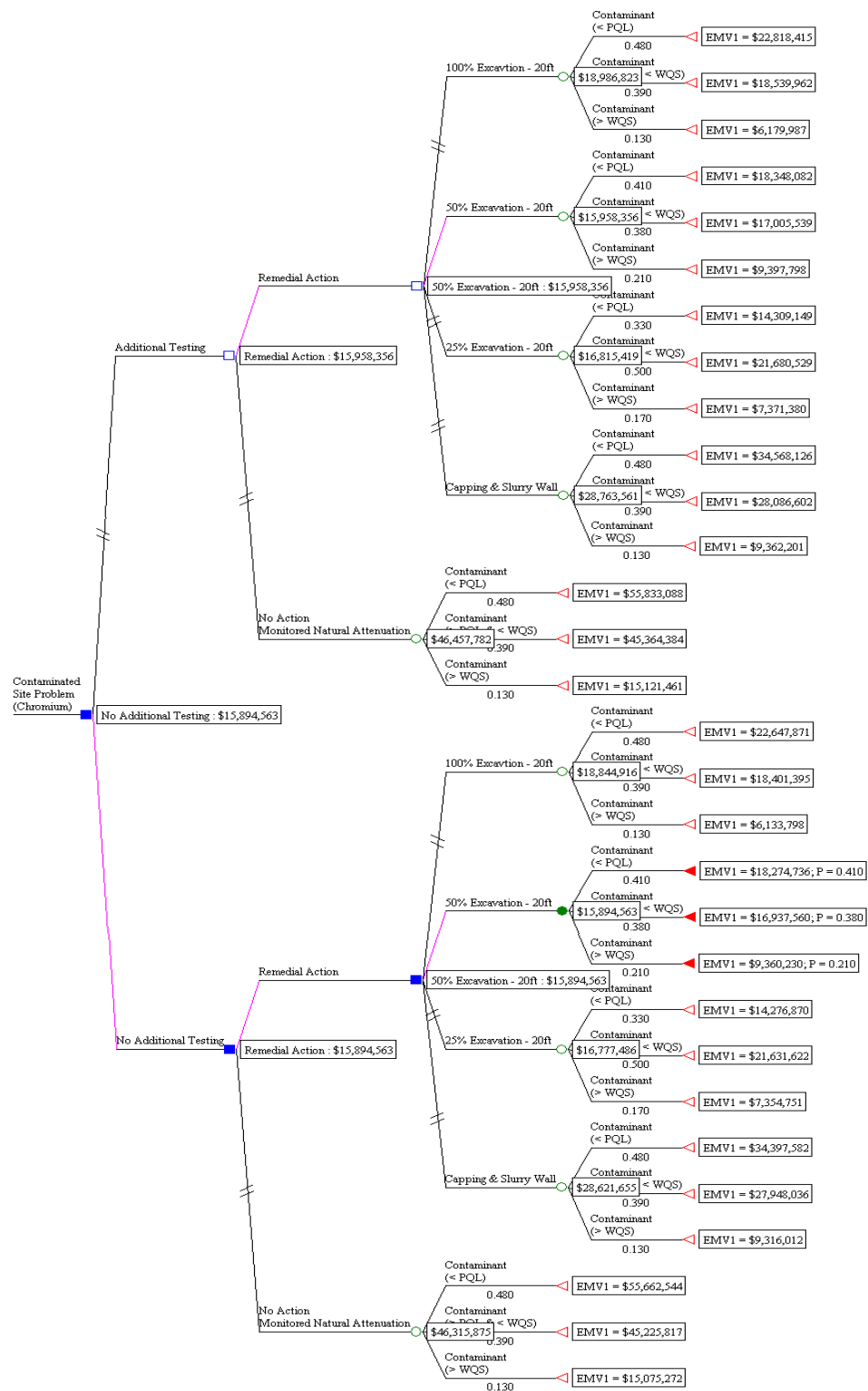


Figure 4-13: Decision tree for chromium based on 20 ft excavation under Scenario 1

B. Decision Trees for Radioactive Waste and Mixed Waste Handling

Figures 4-14 and 4-15 represent the decision trees based on radioactive waste and mixed waste, respectively, under Scenario 1 and based on 20 ft excavation. In Figure 4-14 (gross alpha), the recommended optimum path is: “No Additional Testing”, take “Remedial Action” by focusing on 25% remediation of the management by "Excavation", with an estimated EMV of \$23.35 million USD. Whereas in Figure 4-15 (mixed waste) the recommended optimum path is: “No Additional Testing”, take “Remedial Action” by focusing on 25% remediation of the management by "Soil Washing", with an estimated of EMV of \$23.66 million USD.

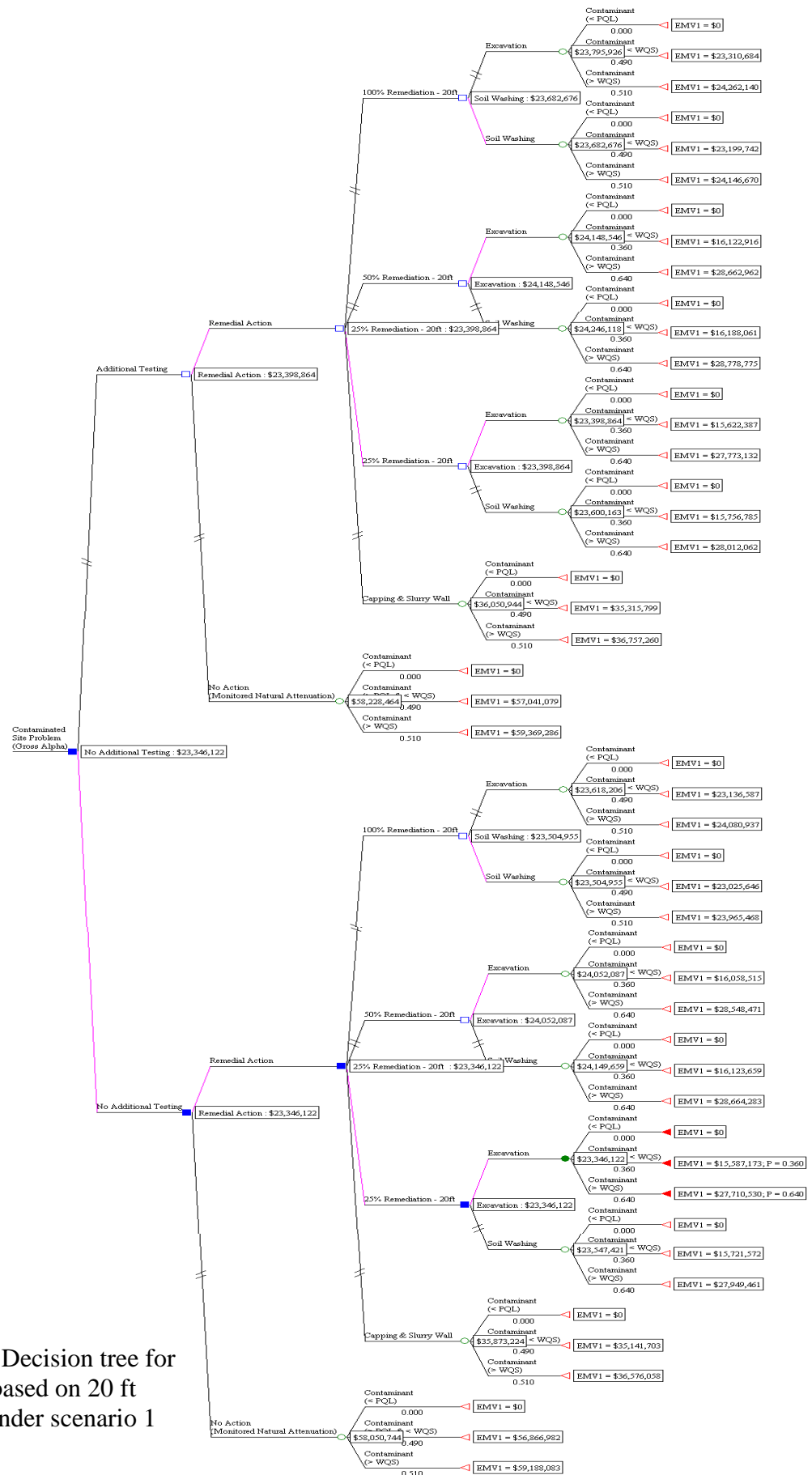


Figure 4-14: Decision tree for gross alpha based on 20 ft excavation under scenario 1

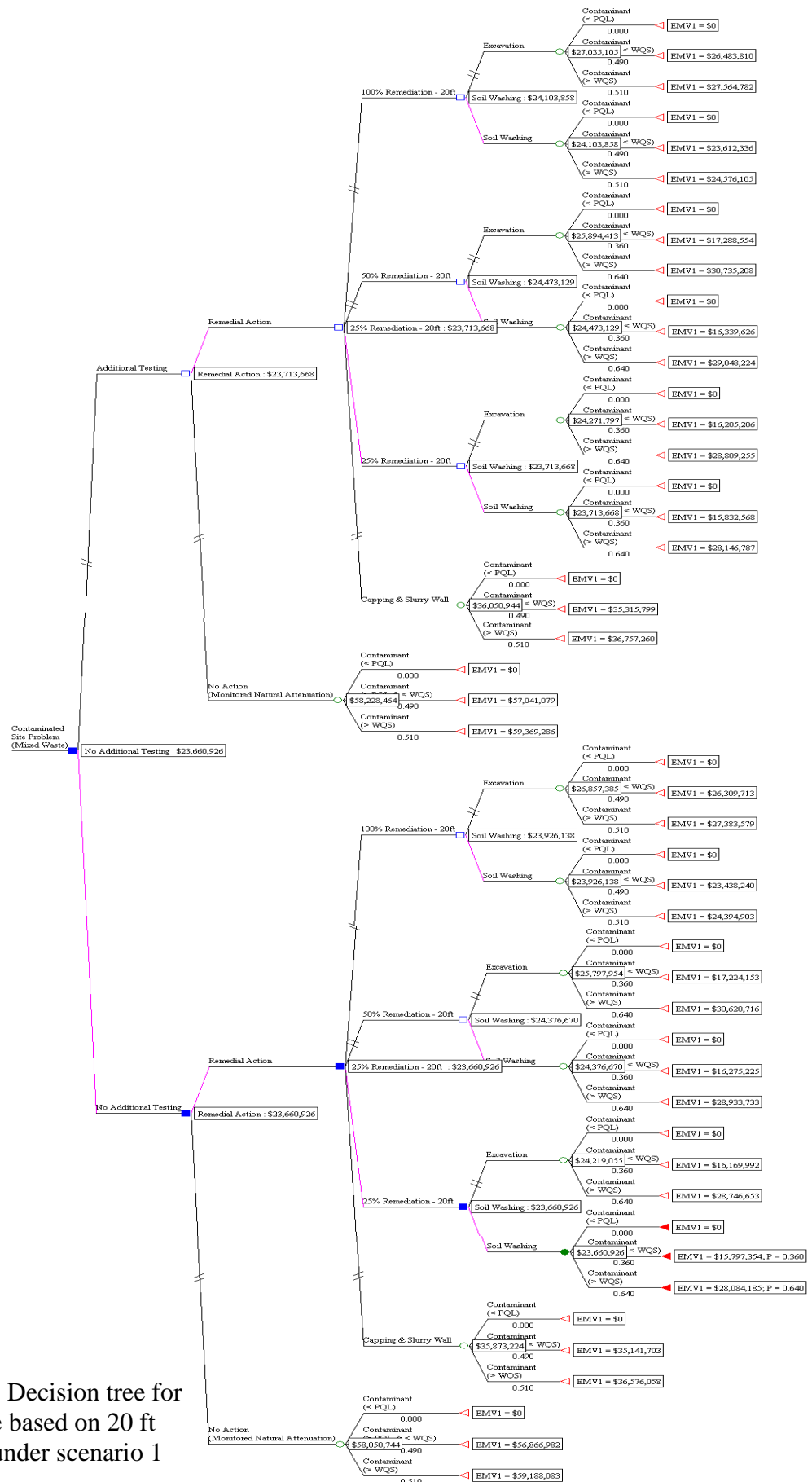


Figure 4-15: Decision tree for mixed waste based on 20 ft excavation under scenario 1

Alternative 2: Design Based on 30 ft Excavation

The decision trees developed under this alternative assume that a maximum depth of 30 ft of contaminated soil will be excavated. Depending on the remediation technology selected, the entire excavated material would either be disposed (in the case of excavation only), or washed before disposing (in the case soil treatment). It also assumes that additional fill would be sourced from elsewhere.

A. Decision Trees for Chemical Waste Handling

Figures 4-16, 4-17 and 4-18 illustrates decision trees that were based on the three chemical CoCs (TCE, EDB and chromium respectively), under Scenario 1 and with only 30 ft of excavation. With reference to Figure 4-16 (TCE), the optimum decision path is indicated by the darkened nodes. The optimum decision path suggested by this tree was to perform “No Additional Testing” and to take “Remedial Action” by 50% excavation of the management area. The optimum EMV recommended is \$25.50 million USD. Figure 4-17 (EDB) on the other hand suggests a different optimum path: perform “No Additional Testing”, take “Remedial Action” by 25% excavation of the management area. The optimum EMV recommended is \$20.57 million USD. Figure 4-18 (chromium) suggests a similar path as Figure 4-11 “No Additional Testing”, take “Remedial Action” by 50% excavation of the management area, with a calculated optimum EMV of \$17.35 million USD.

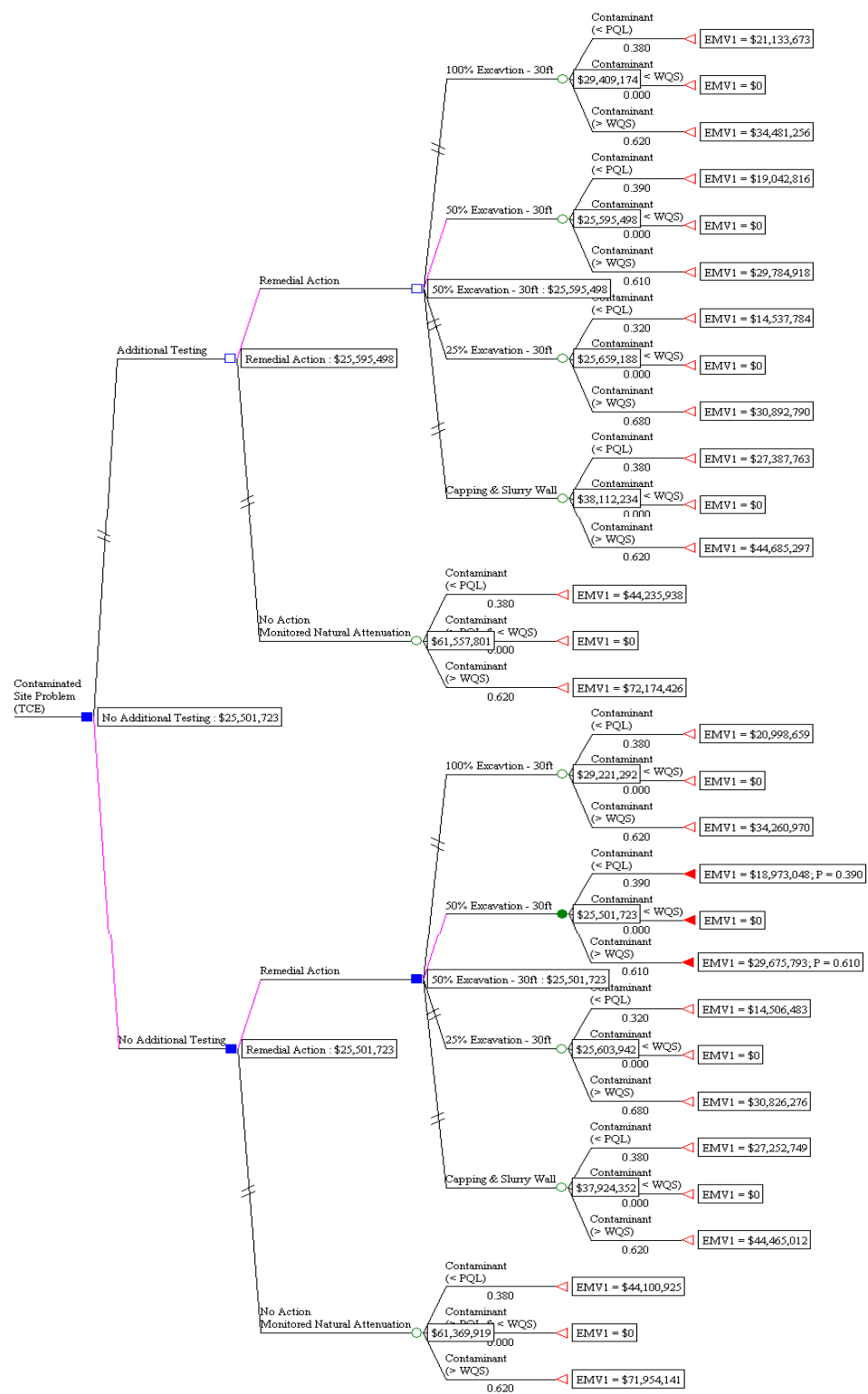


Figure 4-16: Decision tree for TCE based on 30 ft excavation under Scenario 1

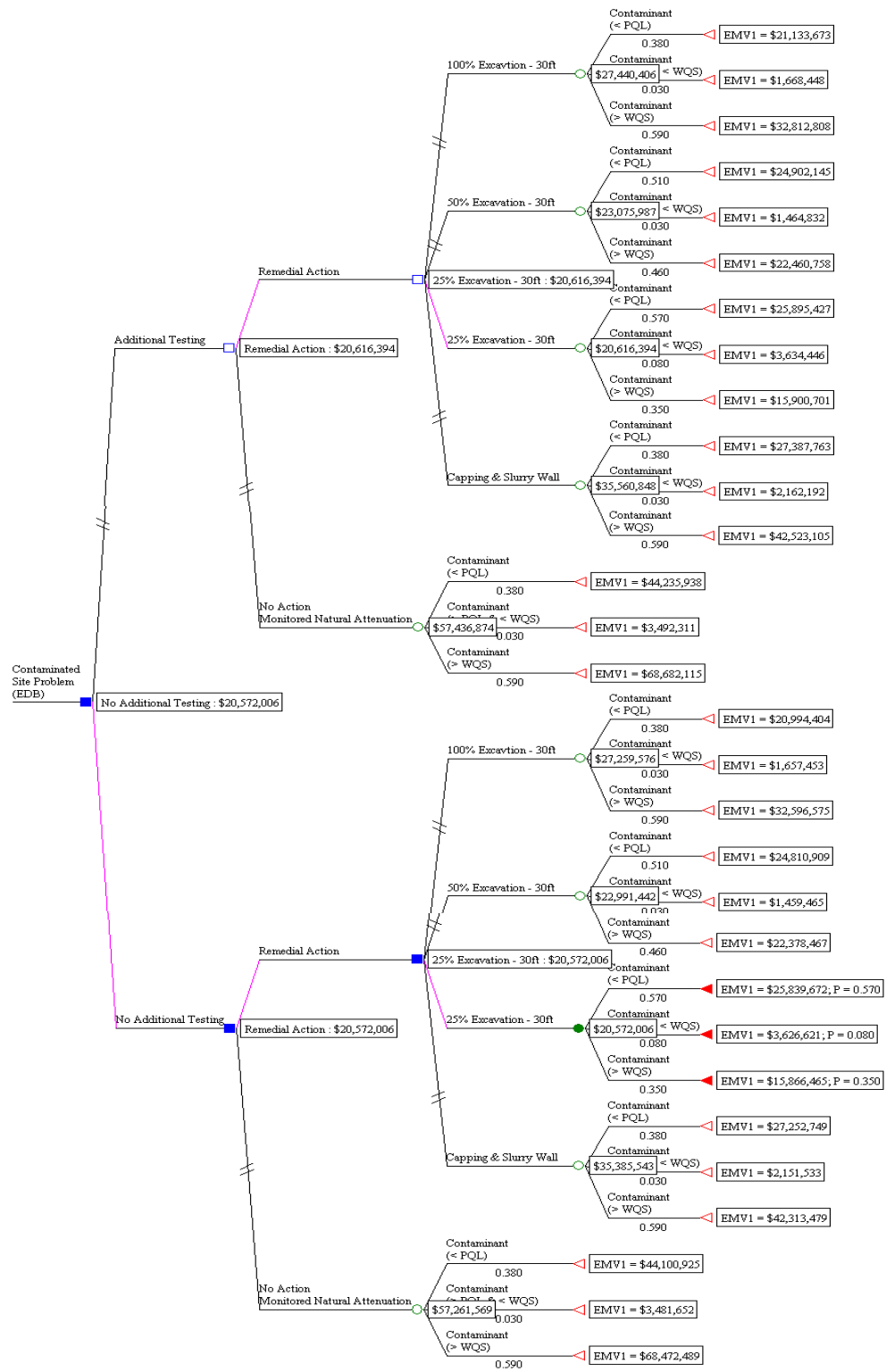


Figure 4-17: Decision tree for EDB based on 30 ft excavation under Scenario 1

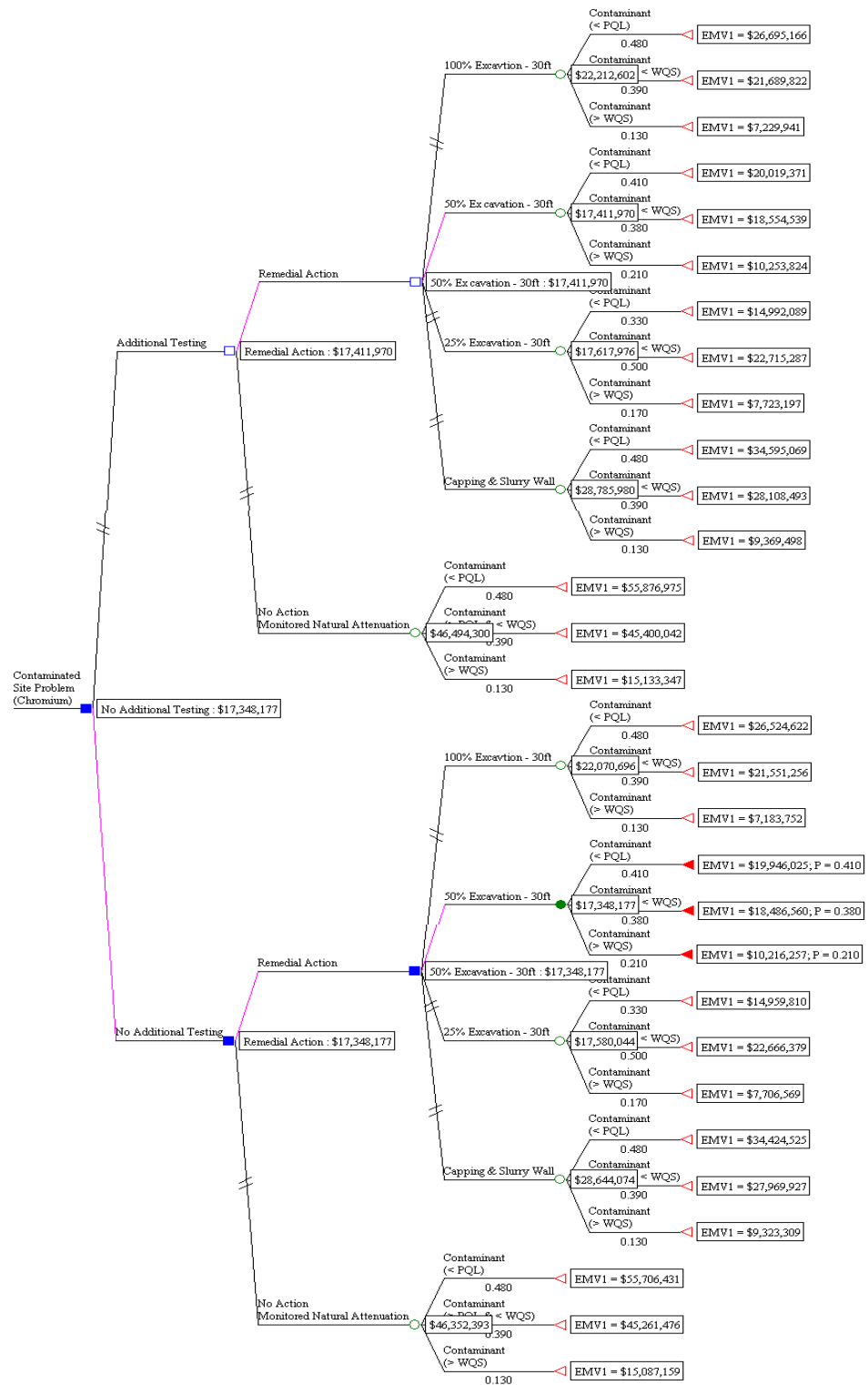


Figure 4-18: Decision tree for Chromium based on 30 ft excavation under Scenario 1

B. Decision Trees for Radioactive Waste and Mixed Waste Handling

Figures 4-19 and 4-20 represent the decision trees based on radioactive waste and mixed waste respectively under Scenario 1 and based on 30 ft excavation. Both trees recommended the same optimum path: “No Additional Testing”, take “Remedial Action” by focusing on 25% remediation of the management by "Soil Washing". Figure 4-19 (gross alpha) calculated an optimum EMV of \$24.44 million USD, whereas Figure 4-20 (mixed waste) resulted in an EMV of \$24.78 million USD.

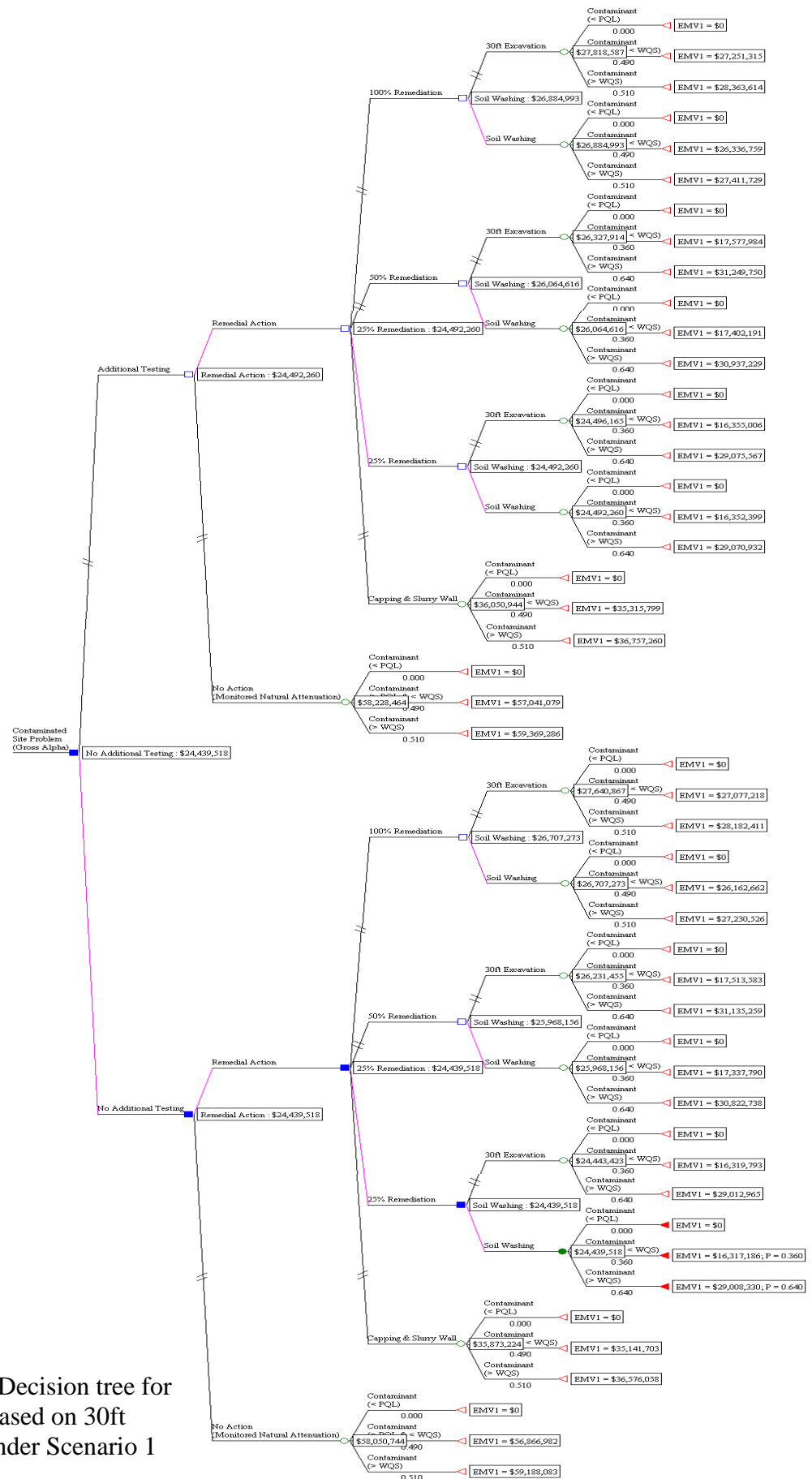


Figure 4-19: Decision tree for gross alpha based on 30ft excavation under Scenario 1

Scenario 2: Failure Assessment before end of Pre-set Post-Remediation Monitoring Period

Figures 4-21 to 4-30 shown below depict the decision trees, optimum decision paths and optimum EMVs developed based on the assumption that failure or success of the site remediation will be assessed one year after excavation and/or soil treatment, and five years after installing cap and slurry wall and monitored natural attenuation.

Alternative 1: Design Based on 20 ft Excavation

The decision trees developed under this alternative assume that only 20 ft contaminated soil would be excavated. The top 10 ft of excavated material would be reused for filling, whereas the bottom 10 ft would either be disposed completely or washed before disposing.

A. Decision Trees for Chemical Waste Handling

Figures 4-21, 4-22 and 4-23 illustrates decision trees that are based on the three chemical CoCs (TCE, EDB and chromium, respectively), under Scenario 2 and with only 20 ft of excavation. With reference to Figure 4-21 (TCE), the optimum decision path is indicated by the darkened nodes. The optimum decision path suggested by this tree was to perform “No Additional Testing” and to take “Remedial Action” by 50% excavation of the management area. The optimum EMV recommended is \$19.55 million USD. Figure 4-22 (EDB) on the other hand suggests a different optimum path: perform “No Additional Testing”, take “Remedial Action” by 25% excavation of the management area. The optimum EMV recommended is \$16.28 million USD. Figure 4-23 (chromium) suggests a similar path as Figure 4-21 “No Additional Testing”, take “Remedial Action” by 50% excavation of the management area, with a calculated optimum EMV of \$13.21 million USD.

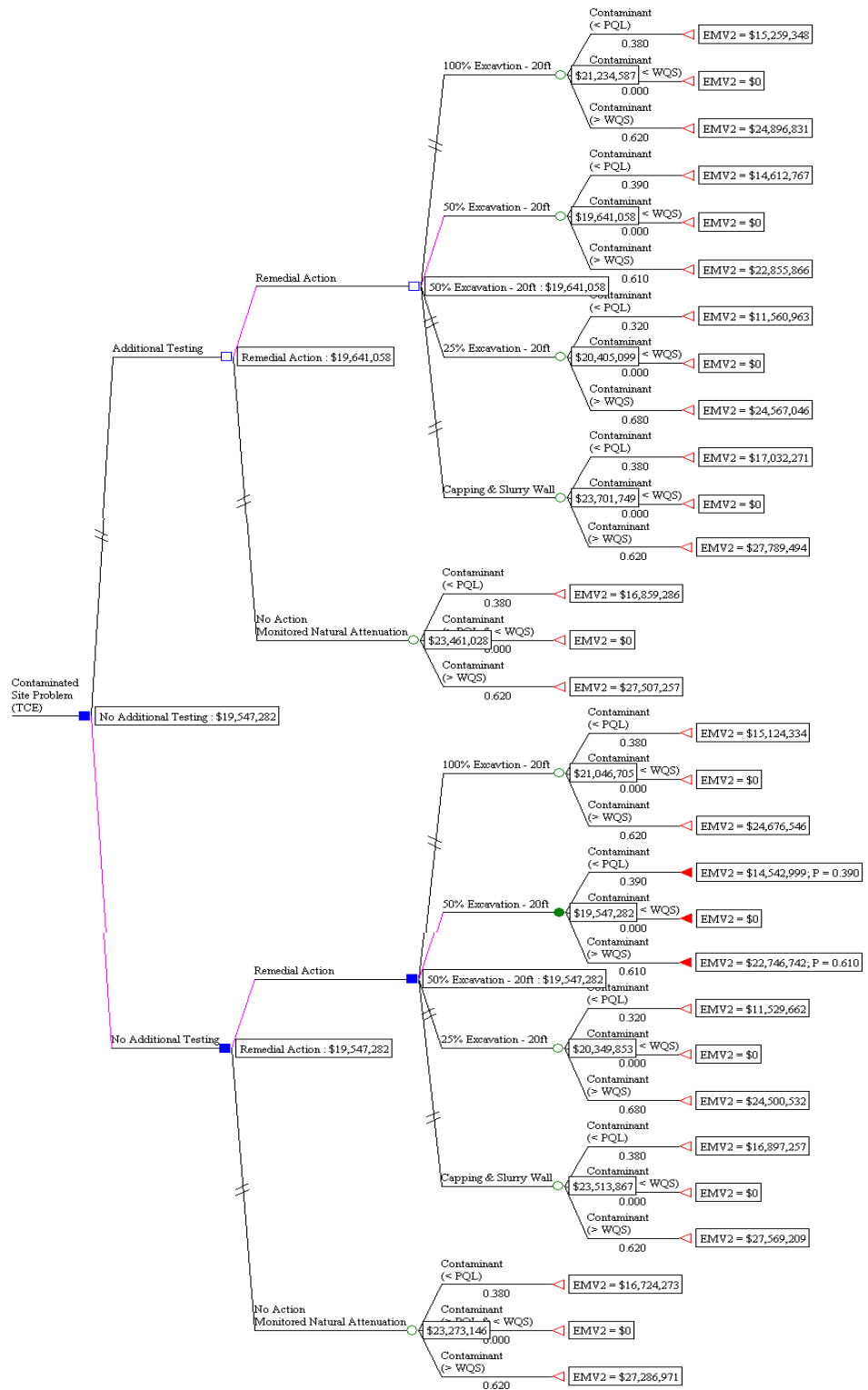


Figure 4-21: Decision tree for TCE based on 20 ft excavation under Scenario 2

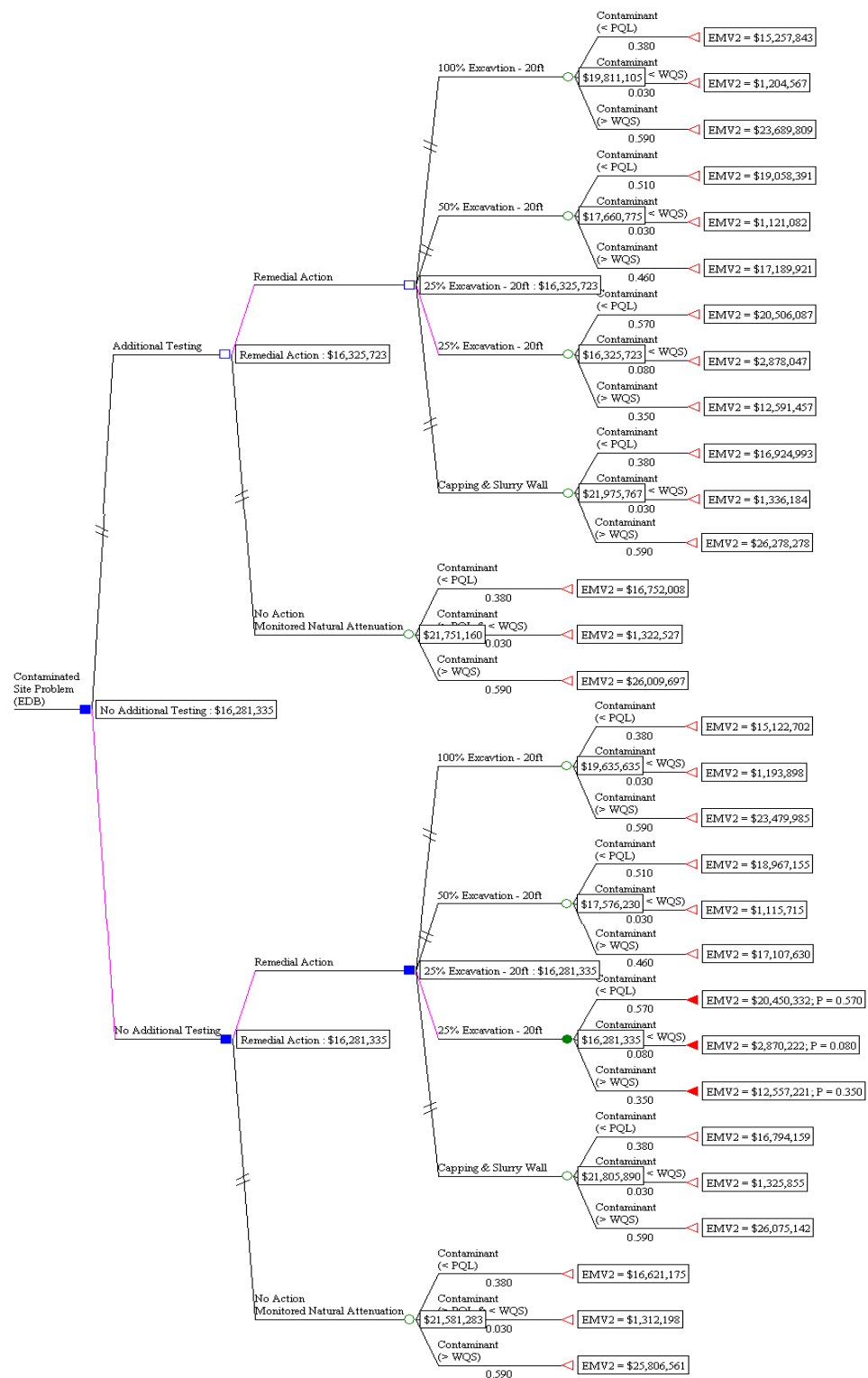


Figure 4-22: Decision tree for EDB based on 20 ft excavation under Scenario 2

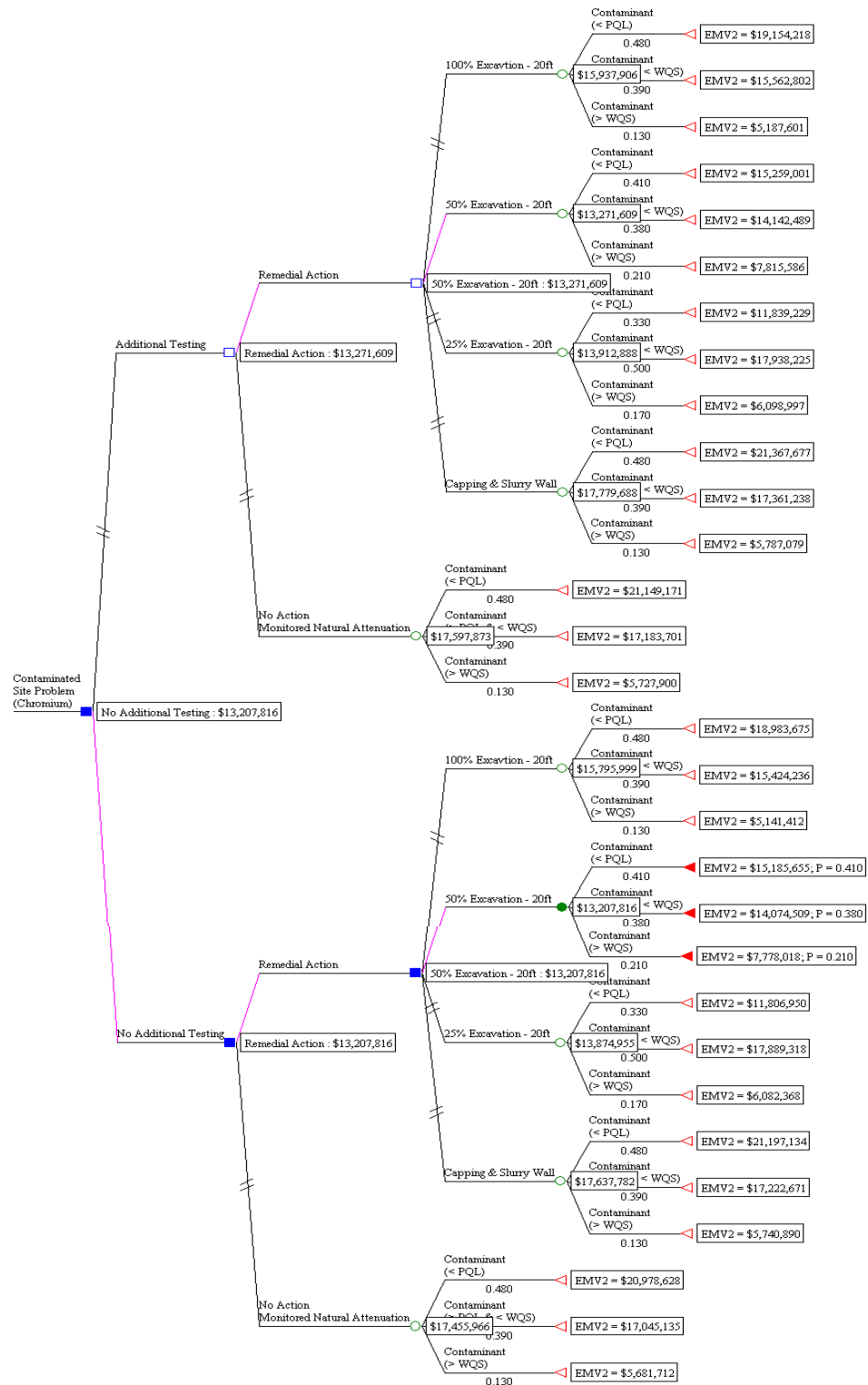


Figure 4-23: Decision tree for chromium based on 20 ft excavation under Scenario 2

B. Decision Trees for Radioactive Waste and Mixed Waste Handling

Figures 4-24 and 4-25 represent the decision trees developed based on radioactive waste and mixed waste, respectively, under Scenario 2 and based on 20 ft excavation. In Figure 4-24 (gross alpha), the recommended optimum path is: “No Additional Testing”, take “Remedial Action” by focusing on 25% remediation of the management by "Excavation", with an estimated EMV of \$19.36 million USD. Whereas in Figure 4-25 (mixed waste) the recommended optimum path is: “No Additional Testing”, take “Remedial Action” by focusing on 25% remediation of the management by "Soil Washing", with an estimated of EMV of \$19.62 million USD.

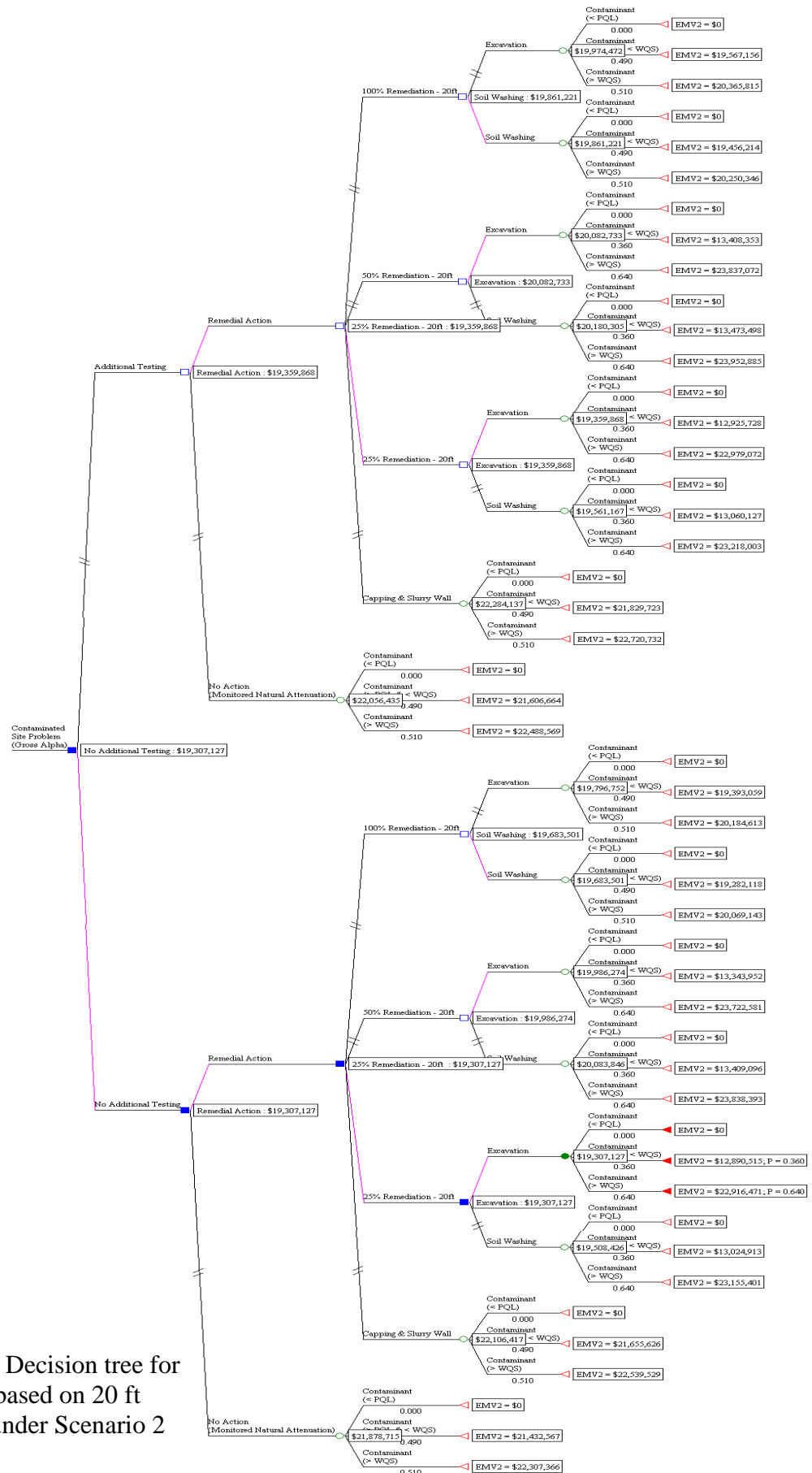


Figure 2-24: Decision tree for gross alpha based on 20 ft excavation under Scenario 2

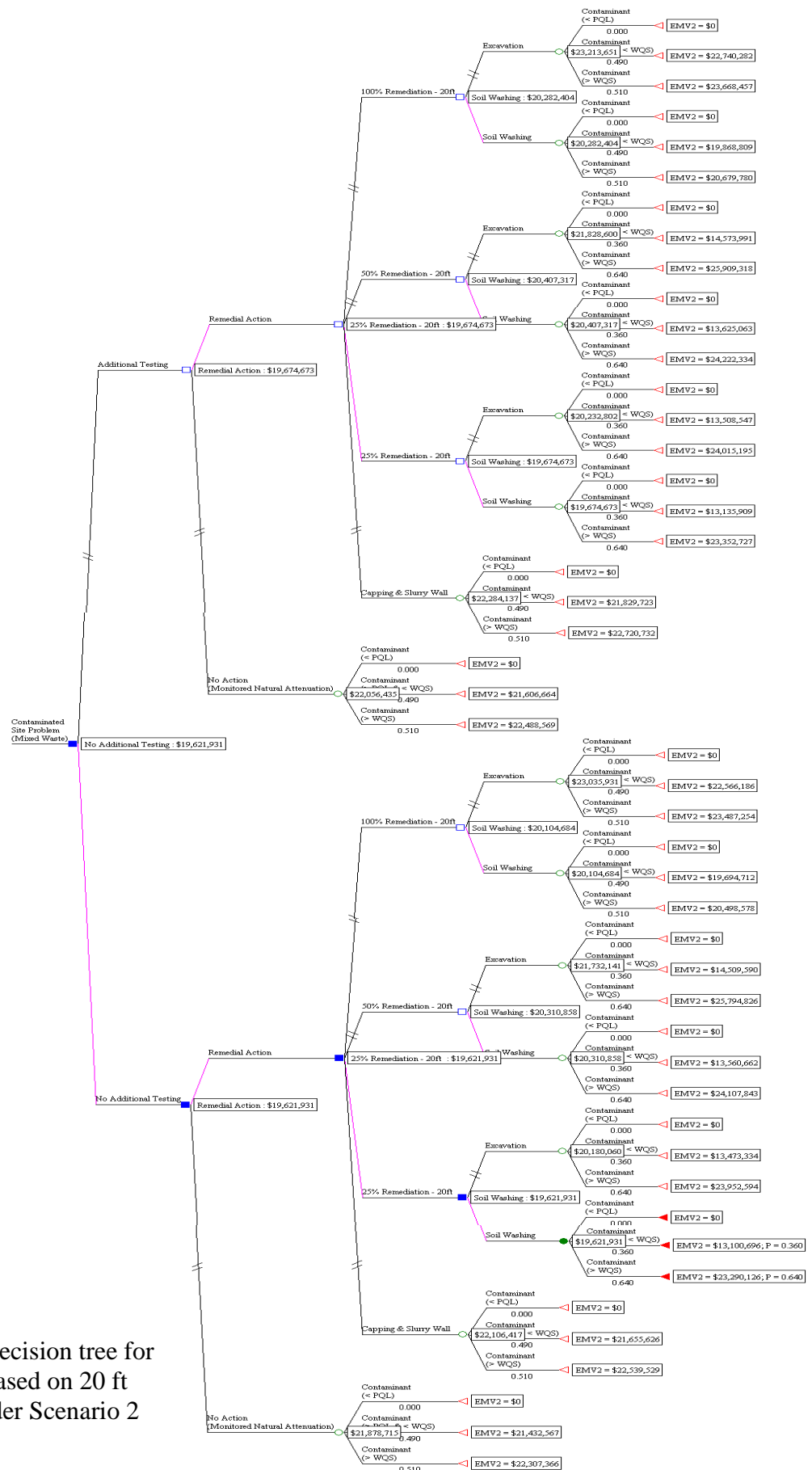


Figure 2-25: Decision tree for mixed waste based on 20 ft excavation under Scenario 2

Alternative 2: Design Based on 30 ft Excavation

The decision trees developed under this alternative assume that a maximum depth of 30 ft of contaminated soil will be excavated. Depending on the selected remediation technology selected, the entire excavated material would either be disposed in the case of excavation only, or washed before disposing in the case soil treatment. It also assumes that additional fill would be sourced from elsewhere.

A. Decision Trees for Chemical Waste Handling

Figures 4-26, 4-27 and 4-28 illustrates decision trees that are based on the three chemical CoCs (TCE, EDB and chromium, respectively), under Scenario 2 and with only 30 ft of excavation. With reference to Figure 4-26 (TCE), the optimum decision path is indicated by the darkened nodes. The optimum decision path suggested by this tree was to perform “No Additional Testing” and to take “Remedial Action” by 25% excavation of the management area. The optimum EMV recommended is \$21.38 million USD. Figure 4-27 (EDB) on the other hand suggests a different optimum path: perform “No Additional Testing”, take “Remedial Action” by 25% excavation of the management area. The optimum EMV recommended is \$17.21 million USD. Figure 4-28 (chromium) recommends a different path from Figures 4-26 and 4-27 “No Additional Testing”, take “Remedial Action” by 50% excavation of the management area, with a calculated optimum EMV of \$14.66 million USD.

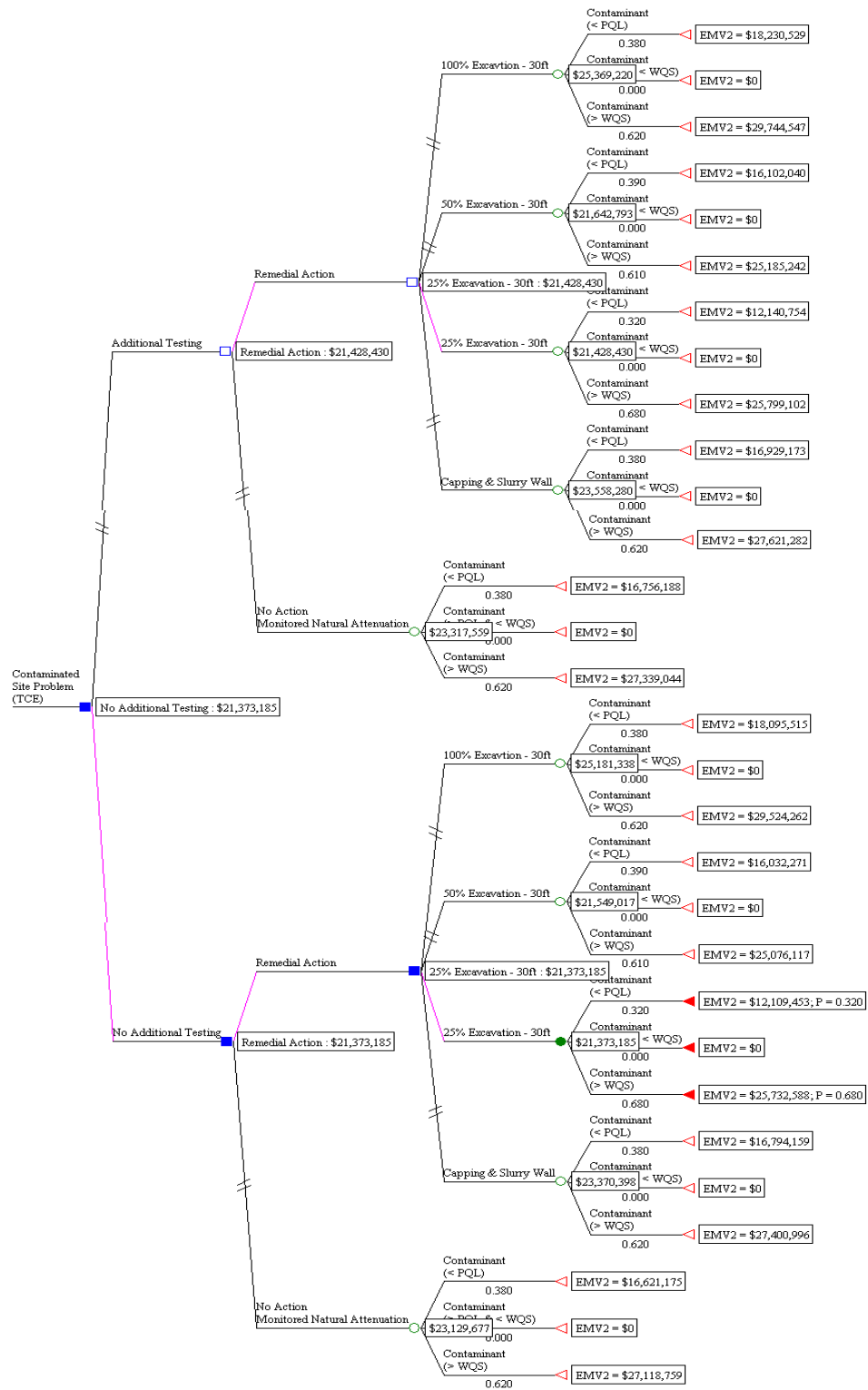


Figure 4-26: Decision tree for TCE based on 30 ft excavation under Scenario 2

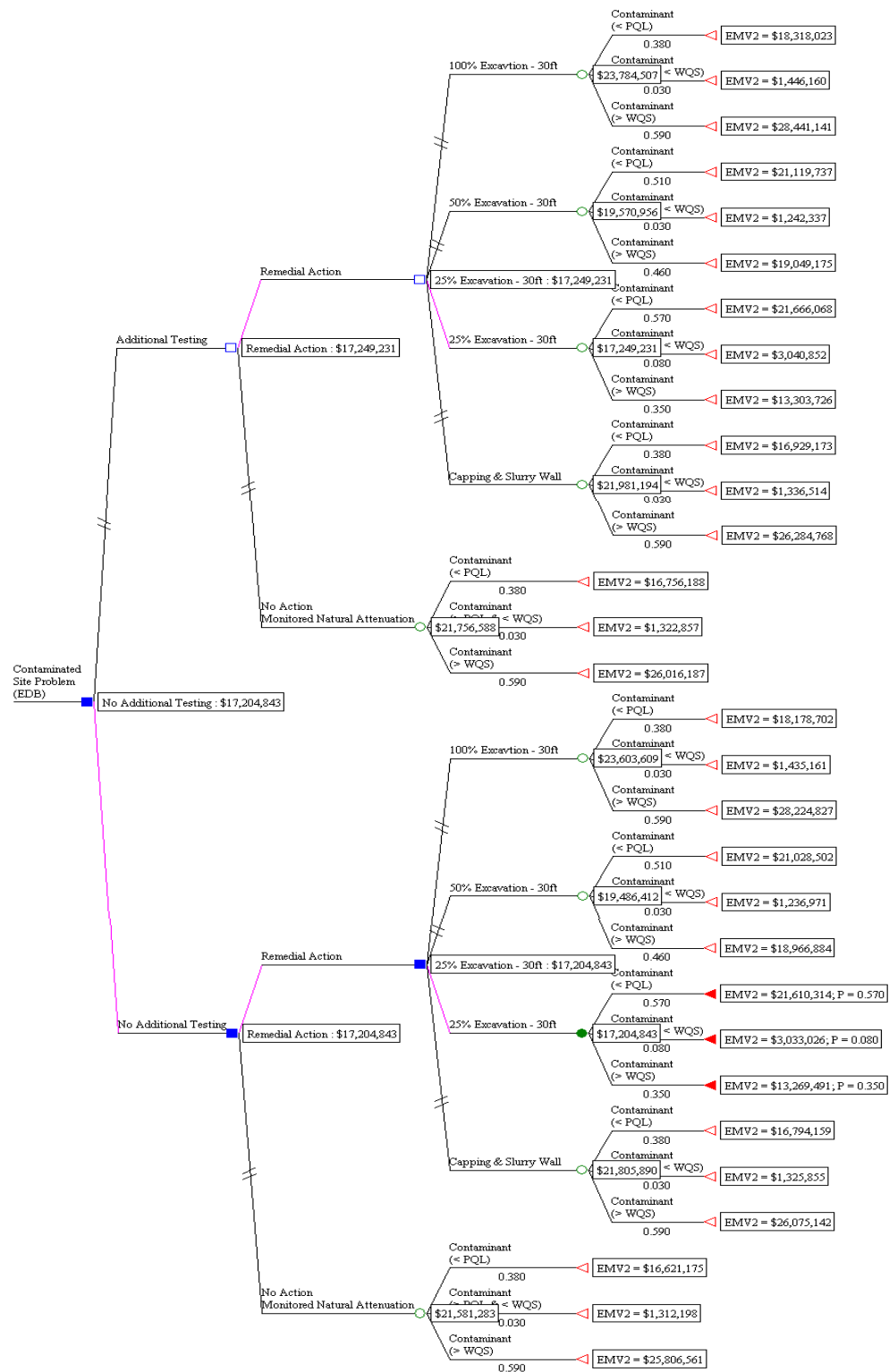


Figure 4-27: Decision tree for EDB based on 30 ft excavation under Scenario 2

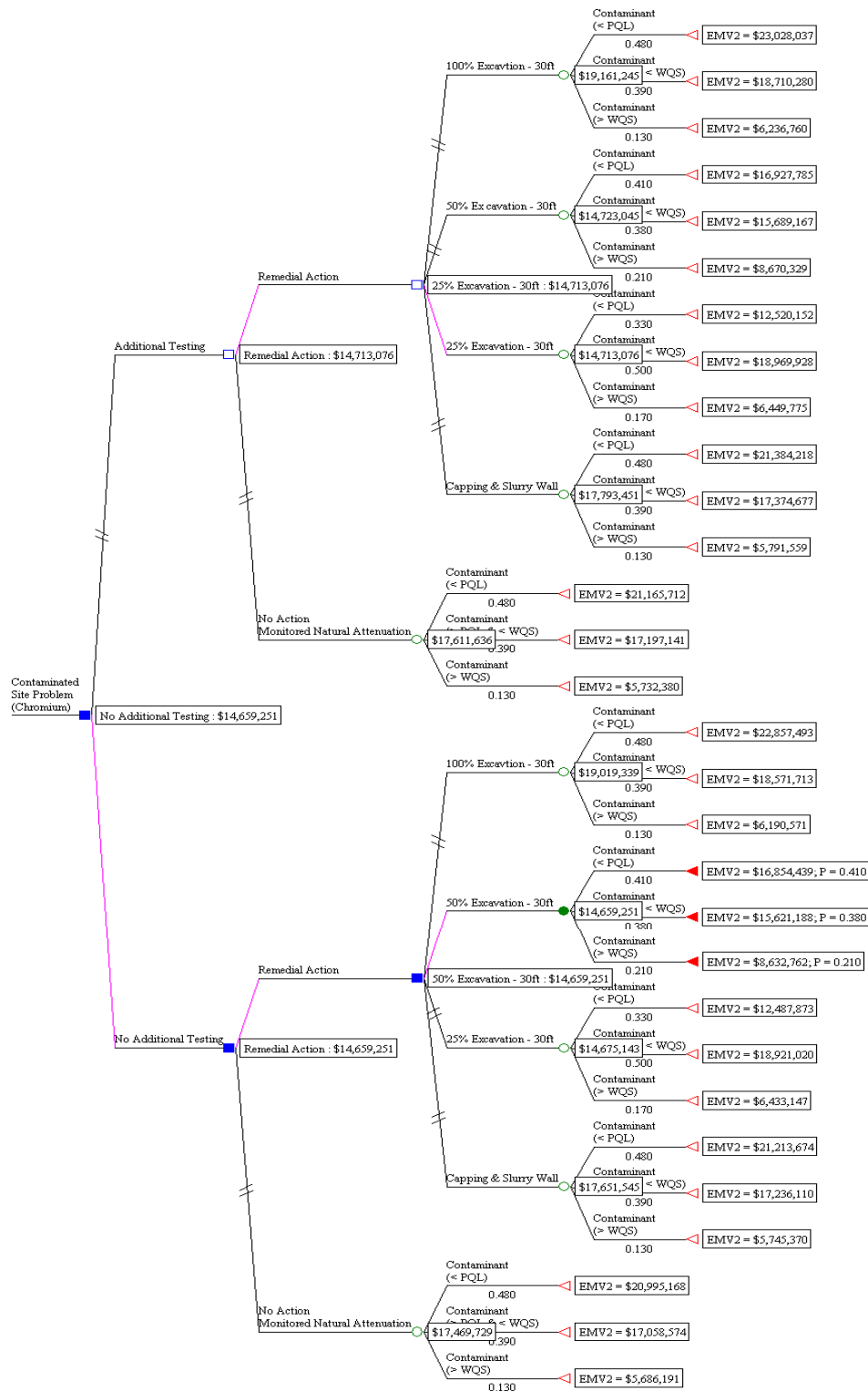


Figure 4-28: Decision tree for Chromium based on 30 ft excavation under Scenario 2

B. Decision Trees for Radioactive Waste and Mixed Waste Handling

Figures 4-29 and 4-30 represent the decision trees developed based on radioactive waste and mixed waste, respectively, under Scenario 2 and based on 30 ft excavation. Both trees recommend the same optimum path: “No Additional Testing”, take “Remedial Action” by focusing on 25% remediation of the management by "Soil Washing". Figure 4-29 (gross alpha) calculated an optimum EMV of \$20.41 million USD, whereas Figure 4-30 (mixed wasted) resulted in a EMV of \$20.71 million USD.

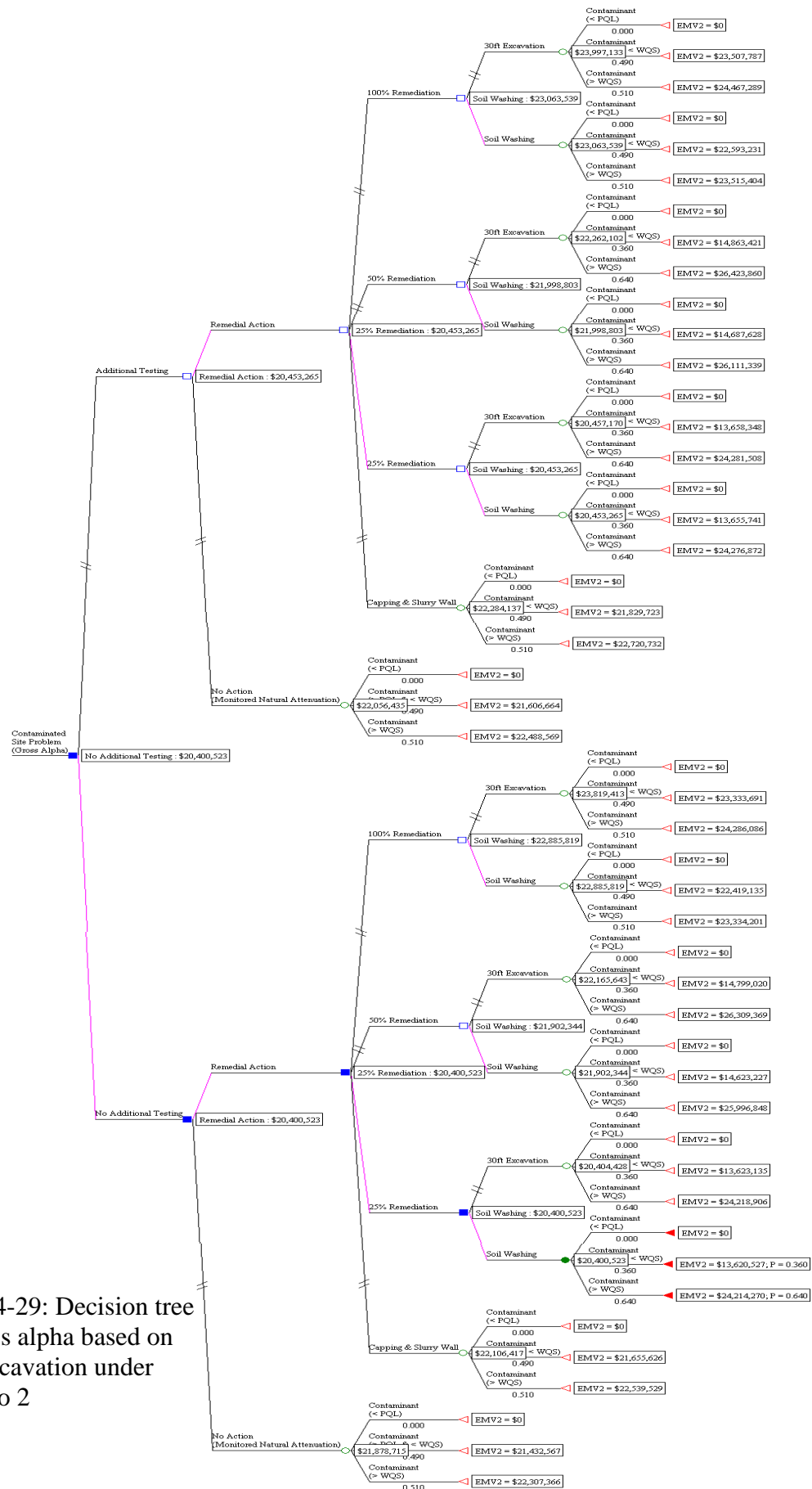


Figure 4-29: Decision tree for gross alpha based on 30 ft excavation under Scenario 2

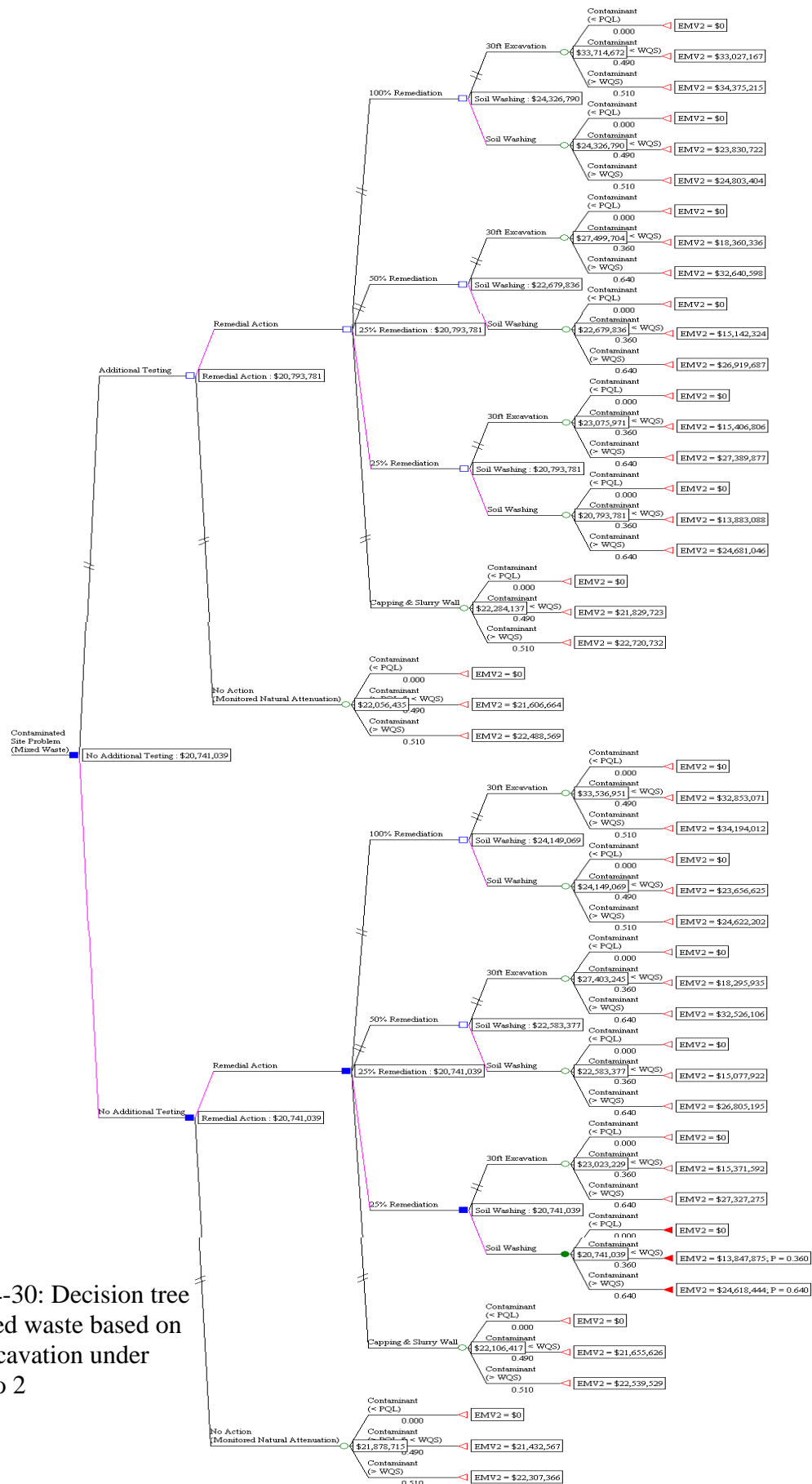


Figure 4-30: Decision tree for mixed waste based on 30 ft excavation under Scenario 2

CHAPTER V

DISCUSSION OF RESULTS AND RECOMMENDATIONS

Discussion of Results

This chapter discusses the outcomes of the decision trees presented in Chapter IV (Figures 4-11 to 4-30), with emphasis on alternatives with greater probability of meeting satisfactory remediation objectives. However, the final decision of what remedial option is to be applied to the contaminated site problem remained subject to deliberation and consensus between the OSU remediation planning team and the regulatory body requesting the clean-up, the Oklahoma Department of Environmental Quality (ODEQ).

A case study was presented in Chapter II to which the decision analysis methodology was applied. Given the complexity of the situation and the decision required, decision tree analysis methodology was adapted to the problem to evaluate the various hypothetical scenarios and alternatives that were considered in choosing the most effective remedial action plan for cleaning up the contaminated burial site.

As mentioned in Chapters III and IV, three chemicals (TCE, EDB and chromium), one (1) radioactive substance (gross alpha), and a combination of both (mixed waste) were analyzed separately and used as bases for estimating and comparing expected monetary values (EMVs). The EMV estimates for each category of CoC (chemical, radioactive and mixed) within similar scenarios and under the same conditions were compared to each other to determine the most suitable remediation process to be recommended.

Table 3-1 lists the concentration of CoCs detected at each well in May of 2009. The table showed that of the three chemical CoCs, TCE was the most prevalent, having been detected at three wells at concentrations higher than the allowable water quality standard (WQS). This observation pointed to the fact that if remediation planning was to be focused on chemical cleaning alone, then TCE would be a good representative contaminant to consider, given that it was detected more than any other chemical. A comparison of the EMV estimates for the three CoCs also attest to this recommendation. Remediation of TCE was found to be more expensive than any of the other two chemical CoCs. Tables 5-1 and 5-2 summarize the EMV estimates for 20 ft and 30 ft remediation, respectively, based on the chemical CoCs, highlighting the optimum values with ***bold-italics***.

Table 5-1: Summary of EMV estimates based on Chemical CoCs with 20 ft excavation

		TCE		EDB		Chromium	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
		EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)
25% Exc.	W. Testing	24,663,025.0 0	20,405,099.0 0	19,692,886.0 0	16,325,723.0 0	16,815,419.0 0	13,912,888.0 0
	W/O Testing	24,607,779.0 0	20,349,853.0 0	<i>19,648,498.0 0</i>	<i>16,281,335.0 0</i>	16,777,486.0 0	13,874,955.0 0
50% Exc.	W. Testing	23,618,979.0 0	19,641,058.0 0	21,165,806.0 0	17,660,775.0 0	15,958,419.0 0	13,271,609.0 0
	W/O Testing	<i>23,525,203.0 0</i>	<i>19,547,282.0 0</i>	21,081,261.0 0	17,576,230.0 0	<i>15,894,563.0 0</i>	<i>13,207,816.0 0</i>
100% Exc.	W. Testing	25,299,978.0 0	21,234,587.0 0	23,467,004.0 0	19,811,105.0 0	18,986,823.0 0	15,937,906.0 0
	W/O Testing	25,112,096.0 0	21,046,705.0 0	23,291,601.0 0	19,635,635.0 0	18,844,916.0 0	15,795,999.0 0
Cap & S/Wall	W. Testing	38,345,930.0 0	23,701,749.0 0	35,555,420.0 0	21,975,767.0 0	28,763,561.0 0	17,779,688.0 0
	W/O Testing	38,158,048.0 0	23,513,867.0 0	35,385,543.0 0	21,805,890.0 0	28,621,655.0 0	17,637,782.0 0
MNA	W. Testing	61,938,467.0 0	23,461,028.0 0	57,431,446.0 0	21,751,160.0 0	46,457,782.0 0	17,597,873.0 0
	W/O Testing	61,750,585.0 0	23,273,146.0 0	57,261,569.0 0	21,581,283.0 0	46,315,875.0 0	17,455,966.0 0

- Scenario 1 is based on estimation of failure cost after five years for excavation; fifteen years for cap & slurry wall, and twenty five years for MNA.
- Scenario 2 is based on estimation of failure cost after one year for excavation, and five years for both cap & slurry wall, and MNA.

Tables 5-1 and 5-2 generally show that the EMV estimate reduces significantly from Scenario 1 to Scenario 2, ranging from 13% to 63% in some cases. The implication of this is that the longer the post-remediation monitoring duration lasts, the more the costs that are likely to be incurred, if the remediation program eventually fails. Also, comparing EMVs of options with testing (W. Testing) to those without testing (W/O Testing), a slight difference in cost was observed. These differences, although not much in comparison to the actual EMVs (0.22% to 0.30%), can be avoided by eliminating any additional testing plans. However, additional testing may reveal information about the site that could lead to a more precise remediation design and ultimately a less expensive alternative.

Table 5-2: Summary of EMV estimates based on Chemical CoCs with 30 ft excavation

		TCE		EDB		Chromium	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
		EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)
25% Exc.	W. Testing	25,659,188.00	21,428,430.00	20,616,394.00	17,249,231.00	17,617,976.00	14,713,076.00
	W/O Testing	25,603,942.00	21,373,185.00	20,572,006.00	17,204,843.00	17,580,044.00	14,675,143.00
50% Exc.	W. Testing	25,595,498.00	21,642,793.00	23,075,987.00	19,570,956.00	17,411,970.00	14,723,045.00
	W/O Testing	25,501,723.00	21,549,017.00	22,991,442.00	19,486,412.00	17,348,177.00	14,659,251.00
100% Exc.	W. Testing	29,409,174.00	25,369,220.00	27,440,406.00	23,784,507.00	22,212,602.00	19,161,245.00
	W/O Testing	29,221,292.00	25,181,338.00	27,259,576.00	23,603,609.00	22,070,096.00	19,019,339.00
Cap & S/Wall	W. Testing	38,112,234.00	23,558,280.00	35,560,848.00	21,981,194.00	28,785,980.00	17,793,451.00
	W/O Testing	37,924,352.00	23,370,398.00	35,385,543.00	21,805,890.00	28,644,074.00	17,651,545.00
MNA	W. Testing	61,557,801.00	23,317,559.00	57,436,874.00	21,756,588.00	46,494,300.00	17,611,636.00
	W/O Testing	61,369,919.00	23,129,677.00	57,261,596.00	21,581,283.00	46,352,393.00	17,469,729.00

- Scenario 1 is based on estimation of failure cost after five years for excavation; fifteen years for cap & slurry wall, and twenty five years for MNA.
- Scenario 2 is based on estimation of failure cost after one year for excavation, and five years for both cap & slurry wall, and MNA.

Comparing EMVs from the three CoCs, TCE was observed to require a higher cost of treatment than both EDB and chromium, because of its distribution around the site and the concentrations at which it was observed to be occurring. It therefore meant that if the decision makers decided to base remediation on chemical wastes alone, then by focusing remediation activities on TCE alone, all other chemical contaminants will be addressed as well. Finally, observe in Tables 5-1 and 5-2 that for some scenarios, the 50% rather than 25% EMVs are highlighted as the lowest (optimal) options. This depicts that the optimal path is not necessarily that of the smallest treatment area considered (i.e. 25%), but rather is estimated based on a combination of EMVs of individual states of nature under each scenario, based on the weight of its probability. Based on these, if decision makers/site managers decided to treat the entire management area as a chemical only waste site, then it is recommended that:

- (1) The EMV estimates based on TCE be considered,
- (2) For Scenario 1, 50% excavation of management should be implemented regardless of the depth to be excavated,
- (3) For Scenario 2, 50% of management area be excavated if only 20 ft is to be excavated and 25% if 30 ft,
- (4) Prolonged post-monitoring duration period be avoided and failure assessment implemented as soon as possible. This can result in significant remedial cost minimization.

Ultimately, as previously mentioned, the final recommendations would depend on a consensus reached between the responsible party (Oklahoma State University – OSU), and the regulatory agency (Oklahoma Department of Environmental Quality – ODEQ).

Tables 5-3 and 5-4 summarize the EMV estimates for 20 ft and 30 ft remediation respectively, based on the radioactive CoC (gross alpha) and mixed waste treatment, highlighting the optimum values. Note that each excavation alternative included in these tables contains an additional row showing the EMV estimates based on soil treatment. Soil treatment is not included as a remediation option in the chemical CoCs analysis because it is a technology specifically recommended for soils contaminated with low level radioactive materials (RACER, 2008). Generally, the EMV estimates reduce significantly from Scenario 1 to Scenario 2, ranging from 10% in some cases to 63% in others. The implication of this is that the longer the post-remediation monitoring duration, the more expenses will be incurred. Comparing EMVs of options with testing (W. Testing) to those without testing (W/O Testing), a slight difference in cost was observed. These differences, although not much in comparison to the actual EMVs (0.22% to 0.30%), can be avoided by eliminating plans to carry out any additional testing.

Comparing the EMVs for excavation and disposal only versus excavation, soil treatment and disposal, a trend was observed. The cost effectiveness of soil treatment as compared to other methods increased with the volume of soil to be treated. At lower volumes the relative cost effectiveness of the technique decreased considerably. For example, compared to the 100% alternative, applying soil treatment to 50% and 25% of the management area proved to be less economical. In other words, unless the entire management area was to be excavated up to 30 ft, soil washing would not be beneficial.

Table 5-3: Summary of EMV estimates based on Radioactive CoC and mixed waste with 20 ft excavation

			Gross Alpha		Mixed Waste	
			Scenario 1	Scenario 2	Scenario 1	Scenario 2
			EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)
25% Exc.	Excavation	W. Testing	23,398,864.00	19,359,868.00	24,271,797.00	20,232,802.00
		W/O Testing	23,346,122.00	19,307,127.00	24,219,055.00	20,180,060.00
	Soil Treatment	W. Testing	23,600,163.00	19,561,167.00	23,713,668.00	19,674,673.00
		W/O Testing	23,547,421.00	19,508,426.00	23,660,926.00	19,621,931.00
50% Exc.	Excavation	W. Testing	24,148,546.00	20,082,733.00	25,894,413.00	21,828,600.00
		W/O Testing	24,052,087.00	19,986,274.00	25,797,954.00	21,732,141.00
	Soil Treatment	W. Testing	24,246,118.00	20,180,305.00	24,473,129.00	20,407,317.00
		W/O Testing	24,149,659.00	20,083,846.00	24,376,670.00	20,310,858.00
100% Exc.	Excavation	W. Testing	23,795,926.00	19,974,472.00	27,035,105.00	23,213,651.00
		W/O Testing	23,618,206.00	19,796,752.00	26,857,385.00	23,035,931.00
	Soil Treatment	W. Testing	23,682,676.00	19,861,221.00	24,103,858.00	20,282,404.00
		W/O Testing	23,504,955.00	19,683,501.00	23,926,138.00	20,104,684.00
Cap & S/Wall		W. Testing	36,050,944.00	22,284,137.00	36,050,944.00	22,284,137.00
		W/O Testing	35,873,224.00	22,106,417.00	35,873,224.00	22,106,417.00
MNA		W. Testing	58,228,464.00	22,056,435.00	58,228,464.00	22,056,435.00
		W/O Testing	58,050,744.00	21,878,715.00	58,050,744.00	21,878,715.00

- Scenario 1 is based on estimation of failure cost after five years for both excavation and soil washing; fifteen years for cap & slurry wall, and twenty five years for MNA.
- Scenario 2 is based on estimation of failure cost after one year for both excavation and soil washing, and five years for both cap & slurry wall, and MNA.

The estimates in Tables 5-3 and 5-4 showed mixed waste handling to be significantly more cost intensive than it was for handling radioactive wastes alone, with difference in estimates ranging from \$100 thousand USD to over \$3 million USD, respectively. In terms of single waste treatment (chemical or radioactive), the projected EMV for TCE is recommended as the critical estimate because successful remediation of TCE similarly implies successful remediation of other constituents. However, if the waste were to be determined to be mixed waste, then the appropriate projected EMV for mixed waste is

recommended as a basis for remediation planning.

Table 5-4: Summary of EMV estimates based on Radioactive CoC and mixed waste with 30 ft excavation

			Gross Alpha		Mixed Waste	
			Scenario 1	Scenario 2	Scenario 1	Scenario 2
			EMV (USD)	EMV (USD)	EMV (USD)	EMV (USD)
25% Exc.	Excavation	W. Testing	24,496,165.00	20,457,170.00	27,114,966.00	23,075,971.00
		W/O Testing	24,443,423.00	20,404,428.00	27,062,224.00	23,023,229.00
	Soil Treatment	W. Testing	24,492,260.00	20,453,265.00	24,832,776.00	20,793,781.00
		W/O Testing	24,439,518.00	20,400,523.00	24,780,034.00	20,741,039.00
50% Exc.	Excavation	W. Testing	26,327,914.00	22,262,102.00	31,565,516.00	27,499,704.00
		W/O Testing	26,231,455.00	22,165,643.00	31,469,057.00	27,403,245.00
	Soil Treatment	W. Testing	26,064,616.00	21,998,803.00	26,745,648.00	22,679,836.00
		W/O Testing	25,968,1156.00	21,902,344.00	26,649,189.00	22,583,377.00
100% Exc.	Excavation	W. Testing	27,818,587.00	23,997,133.00	37,536,126.00	33,714,672.00
		W/O Testing	27,640,867.00	23,819,413.00	37,358,405.00	33,536,951.00
	Soil Treatment	W. Testing	26,884,993.00	23,063,539.00	28,148,244.00	24,326,790.00
		W/O Testing	26,707,273.00	22,885,819.00	27,970,523.00	24,149,069.00
Cap & S/Wall	W. Testing	36,050,944.00	22,284,137.00	36,050,944.00	22,284,137.00	
	W/O Testing	35,873,224.00	22,106,417.00	35,873,224.00	22,106,417.00	
MNA	W. Testing	58,228,464.00	22,056,435.00	58,228,464.00	22,056,435.00	
	W/O Testing	58,050,744.00	21,878,715.00	58,050,744.00	21,878,715.00	

- Scenario 1 is based on estimation of failure cost after five years for both excavation and soil washing; fifteen years for cap & slurry wall, and twenty five years for MNA.
- Scenario 2 is based on estimation of failure cost after one year for both excavation and soil washing, and five years for both cap & slurry wall, and MNA.

Recommendations

Overall, since the aim of the decision analysis methodology was to minimize cost while reaching satisfactory treatment levels, it is recommended that the post-remediation monitoring duration period before failure is assessed be limited to the conditions defined for Scenario 2. Based on waste characterization, the recommended EMV estimates and their corresponding present worth values for remediation technology only (in parenthesis) are summarized below:

- For chemical waste (based on TCE):
 - o For the 20 ft excavation option, the optimum alternative was to excavate 50% of the most contaminated area and assess for failure after 1 year with an estimated EMV of \$19.55 million USD (\$2.08 million USD).
 - o For the 30 ft excavation option, the optimum alternative was to excavate 25% of the most contaminated area and assess for failure after 1 year with an estimated EMV of \$21.38 million USD (\$3.10 million USD).
- For radioactive waste (based on gross alpha):
 - o For the 20 ft remediation option, the optimum alternative was to excavate 25% of the most contaminated area and assess for failure after 1 year with an estimated EMV of \$19.31 million USD (\$1.05 million USD).
 - o For the 30 ft remediation option, the optimum alternative was to excavate and treat 25% of the most contaminated soil within the management area, and assess for failure after 1 year with an estimated EMV of \$20.41 million USD (\$3.08 million USD).

- For mixed waste:
 - For the 20 ft remediation option, the optimum alternative was to excavate and treat 25% of the most contaminated soil within the management area, and assess for failure after 1 year with an estimated EMV of \$19.63 million USD (\$1.63 million USD).
 - For the 30 ft remediation option, the optimum alternative was to excavate and treat 25% of the most contaminated soil within the management area, and assess for failure after 1 year with an estimated EMV of \$20.75 million USD (\$3.71 million USD).

CHAPTER VI

CONCLUSIONS

Summary of Methodology

This study was conducted to develop a decision analysis methodology for remediating a contaminated site. A former waste burial site used by Oklahoma State University to dispose of chemical and low level radioactive wastes which will require site closure proceedings was used as a practical case study.

A decision tree approach was used as the methodology to identify optimum alternatives for remediating the site, under conditions of uncertainty. Uncertainties in extent of subsurface contamination, exact areas with highest contamination, choice of contaminant of concern, remediation methods to be employed, post-remediation monitoring duration and depth of soil to be excavated were addressed by combining and assessing a series of probable scenarios. Present worth values of different scenarios over varying time periods were considered to aid in the selection of the optimum remediation plan for the site.

The objective functions shown in Equation 3-1a to 3-3b were the cost minimization models that incorporated remedial action cost, risk of failure cost, additional testing cost, and post remediation monitoring cost. The objective functions were used to calculate the cost of each decision path within the decision tree for different scenarios.

The remediation action cost, additional testing cost and post-remediation monitoring cost used in the objective function were estimated using the RACER™ model. Risk of failure cost was assumed to be the cost of implementing the most thorough remedial action, which in this case was the cost of excavating 30 ft of contaminated soil within the management area, and handling and disposing the waste as a mixed waste. The decision alternative with the least expected monetary value (EMV) was considered the optimum one.

Summary of Findings

Generally, decision analysis methodology was found to be a very useful environmental management tool that had the capability of providing environmental managers with an optimum approach for a given set of information under conditions of uncertainty. The methodology was found to be versatile and adaptable to different scenarios due to its ability to apply different analytical tools to a given situation, and its ability to incorporate an objective function to allow for different alternatives.

For the study area presented in this report, the following conclusions were drawn:

- Time was a crucial factor in determining the overall cost of the project. The longer the project lingered before commencement and/or the longer the post-remediation monitoring period spanned, the higher the remediation cost requirement.
- The optimal decision depended on how the waste was categorized, handled and disposed. That is, if the wastes at the study site were determined to be “mixed”, final disposal cost will be significantly higher than if separate hazardous and low level radiological designations are secured.

- The optimum remediation decision also depended on the depth of contaminated soil to be excavated and/or treated:
 - For chemical waste (based on TCE):
 - For the 20 ft excavation option, the optimum alternative was to excavate 50% of the most contaminated area and assess for failure after 1 year with an estimated EMV of \$19.55 million USD (or \$2.08 million USD in terms of present worth value).
 - For the 30 ft excavation option, the optimum alternative was to excavate 25% of the most contaminated area and assess for failure after 1 year with an estimated EMV of \$21.38 million USD (or \$3.10 million USD in terms of present worth value).
 - For radioactive waste (based on gross alpha):
 - For the 20 ft remediation option, the optimum alternative was to excavate 25% of the most contaminated area and assess for failure after 1 year with an estimated EMV of \$19.31 million USD or \$1.05 million USD in terms of current year cost.
 - For the 30 ft remediation option, the optimum alternative was to excavate and treat 25% of the most contaminated soil within the management area, and assess for failure after 1 year with an estimated EMV of \$20.41 million USD (or \$3.08 million USD in terms of present worth value).
 - For mixed waste:
 - For the 20 ft remediation option, the optimum alternative was to excavate and treat 25% of the most contaminated soil within the management area, and

assess for failure after 1 year with an estimated EMV of \$19.63 million USD (or \$1.63 million USD in terms of present worth value).

- For the 30 ft remediation option, the optimum alternative was to excavate and treat 25% of the most contaminated soil within the management area, and assess for failure after 1 year with an estimated EMV of \$20.75 million USD (or \$3.71 million USD in terms of present worth value).

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APPENDICES

SUMMARY OF INPUTS USED FOR ESTIMATING REMEDIATION COST PARAMETERS IN RACER™

RACER INPUTS

Tabulated below are the parameters and conditions specified in RACER to estimate the direct costs of the selected remediation alternatives. There are two types of parameters: General parameters and Technology specific parameters. The general parameters are those inputs that are generic to all the remediation options, whereas the technology specific parameters are those inputs that are peculiar to the various technologies.

General Parameters

S/No	Parameter Description	User Input
1	Primary Media/Waste Type	Soil
2	Secondary Media/Waste Type	Groundwater
3	Primary Contaminant	Rads: Radioactive (Low level) Chems: Semi-Volatile Organic Compounds (SVOCs)
4	Secondary Contaminant	Rads: Semi-Volatile Organic Compounds (SVOCs) Chems: Radioactive (Low level)
5	Setup Method	Stillwater Oklahoma Template – RCRA Corrective Action Program
6	Distance to Site (One-Way)	10 miles (approximately)
7	Safety Level	D. Personal protection should be worn only as a basic work uniform and not on any site with respiratory or skin hazards. Provides minimal protection against respiratory hazards. Coveralls, hard hats, leather or chemical resistant boots/shoes, and safety glasses or chemical splash goggles are required. Personal dosimeters are required also for radioactive sites.
8	Soil Type	Sand-Silt/San-Clay Mixture

The parameters in the table above are all common to all the technologies. Basically, they refer to the database used by RACER when estimating the costs.

Technology Specific Parameters
A: Excavation & Soil Washing

A-1: Excavation Cost Estimation Parameters

S/No	Parameter Description	User Input		
		100%	50%	25%
1	Estimation Method	Area/Depth		
2	Area (Acres)	1.35	0.675	0.3375
3	Excavation Depth (FT)	Two Options: 20 ft (Use 50% or 10 ft as Backfill) 30 ft		
4	Existing Cover	Soil/Gravel		
5	Replacement Cover	Soil/Seeding		
6	Sidewall Protection & Run : Rise	Side Sloping & 1:1 (Default)		
7	% of Excavated material to be used as backfill	20 ft Exc.: 50% 30 ft Exc.: 0%		
8	Source of Additional Fill & Distance	Offsite & 1 mile		
9	Number of Sampling Points	128 (Default)	71 (Default)	40 (Default)
10	Number of Composites Submitted	32 (Default)	18 (Default)	10 (Default)

Notes:

1. Two excavation alternatives are considered:
 - a. Excavate 20 ft of the contaminated area, save the top 10 ft as backfill material and disposing the bottom 10 ft of excavated material.
 - b. Excavate 30 ft of contaminated area and dispose everything
2. It was assumed that the fill materials will be sourced from within a distance no greater than 1 mile from the site, because OSU owns all the surrounding properties.

A-2: Off-Site Transportation and Disposal of Excavated Materials Cost Estimation
Parameters

S/No	Parameter Description	User Input		
		100%	50%	25%
1	Waste Type	Two Alternatives: Radioactive: Low-Level Radioactive Waste Radioactive: Mixed Waste		
2	Waste Form & Condition of Waste	Solid & Bulk to Remain as Bulk		
3	Volume of Bulk Waste (CY)	20 ft Exc.: 21780 30 ft Exc.: 65350	20 ft Exc.: 10890 30 ft Exc.: 32670	20 ft Exc.: 10890 30 ft Exc.: 16335
4	Waste Disposal Location	Energy Solution, UT		
5	Transportation Type	Truck		
6	Truck Distance (One-Way)	1104 Miles (Approximately)		

Notes:

- Two waste disposal alternatives are considered:
 - Disposal of bulk wastes as low-level radioactive waste at an registered facility
 - Disposal of bulk waste as mixed radioactive waste at a registered facility
- For the 20 ft excavation alternative, the volume of waste disposed is equivalent to the volume of the lower 10 ft of excavated materials.
- For the 30 ft excavation alternative, the volume of excavated material is equivalent to the volume of the entire 30 ft of excavated materials.
- The truck distance is an approximation of the travel distance from Stillwater, Oklahoma to Utah, and not the exact distance from the site to the disposal facility.

A-3: Soil Washing Cost Estimation Parameters

S/No	Parameter Description	User Input		
		100%	50%	25%
1	Process Type	Radiological Screening and Soil Washing		
2	Volume of Soil Washed (LCY)	20 ft Exc.: 21780 30 ft Exc.: 65340	20 ft Exc.: 10890 30 ft Exc.: 32670	20 ft Exc.: 5445 30 ft Exc.: 16335
3	Soil Density (LBS/LCY)	2700 (Approximately)		
4	Quantity of Soil Washed (Tons)	20 ft Exc.: 29403 30 ft Exc.: 88209	20 ft Exc.: 14702 30 ft Exc.: 44105	20 ft Exc.: 7351 30 ft Exc.: 22053
5	Hours of Operation/Day	16 (Default)		
6	Hours of Downtime/Day	2 (Default)		
7	Days of Operation/ Week	5 (Default)		
8	Weeks of Operation/ Year	42 (Default)		
9	Surfactant Addition Rate	4lbs/Ton (Default)		
10	Waste Water Volume	2.5 Gal/Ton (Default)		

Notes:

1. Volume of soil to be washed:
 - a. For the 20 ft alternative is equivalent to 10 ft of excavated material
 - b. For the 30 ft alternative is equivalent to entire (30 ft) excavated material

A-4: Cost Estimation Parameters for Off-Site Transportation and Disposal of Fines from Soil Washing

S/No	Parameter Description	User Input		
		100%	50%	25%
1	Waste Type	Two Alternatives: Radioactive: Low-Level Radioactive Waste Radioactive: Mixed Waste		
2	Waste Form/ Condition of Waste	Solid/ Bulk to Remain as Bulk		
3	Volume of Bulk Waste (CY)	20 ft Exc.: 2832 30 ft Exc.: 8494	20 ft Exc.: 1416 30 ft Exc.: 4248	20 ft Exc.: 708 30 ft Exc.: 2124
4	Waste Disposal Location	Energy Solution, UT		
5	Transportation Type	Truck		
6	Truck Distance (One-Way)	1104 Miles		

Notes:

1. Volume of bulk waste to be disposed:
 - a. For the 20 ft alternative is equivalent to 13% of 10 ft of excavated material
 - b. For the 30 ft alternative is equivalent to 13% of entire (30 ft) excavated material

A-5: Groundwater Monitoring Wells Cost Estimation Parameters

S/No	Parameter Description	User Input		
		100%	50%	25%
1	Number of Aquifers	1		
2	Depth to Groundwater	30		
3	Number of Wells	11	8	7
4	Average Well Depth	35 LF		
5	Formation Type	Unconsolidated		
6	Drilling Method	Air Rotary		
7	Well Diameter	2 Inch		
8	Well Construction Material	Stainless Steel		

Notes:

1. Number of wells refers to the number of existing wells contained in the areas analyzed as 100%, 50% and 25% accordingly, excluding MW-1 and not necessarily 100% or 50% or 25% of the existing wells.

A-6: Monitoring Cost Estimation Parameters

S/No	Parameter Description	User Input					
		100%		50%		25%	
1	Media	Groundwater & Subsurface Soil					
2	Groundwater Monitoring:	30 ft					
	Average Sample Depth						
		1 st year	Out years	1 st year	Out years	1 st year	Out years
	Samples per Event	12	12	9	9	8	8
	Number of Events	4	1	4	1	4	1
	Number of Years	1	5	1	5	1	5
	Number of wells/Day	8		8		7	
	Sampling Method	Existing Wells – Low Flow Pumps					
3	Subsurface Soil:						
	Average Sample Depth	30 ft					
		1 st year	Out years	1 st year	Out years	1 st year	Out years
	Samples per Event	135	135	68	68	34	34
	Number of Events	1	1	1	1	1	1
	Number of Years	1	5	1	5	1	5
	Number of Samples/Day	7 (Default)		7 (Default)		7 (Default)	
	Sampling Method	Direct Push Rig (Default)					

Notes:

1. Samples per event refers to the number of samples to be collected during each monitoring exercise
 - a. Groundwater = number of wells within each area (100%/50%/25%), including MW-1
 - b. Soil = sample collected every 25FT x 25FT area
2. Number of Events refers to how many times the monitoring procedure is to be carried out per year
 - a. Groundwater: once quarterly (4 times) in the first year, then once annually for 5 years
 - b. Soil = once in the first year, and once annually for 5 years

A-7: Additional Testing (RCRA Facility Investigation) Cost Estimation Parameters

S/No	Parameter Description	User Input		
		100%	50%	25%
1	Task description	Sampling and Analysis		
2	Site Complexity	Low		
3	Crew Size	2 Field Technicians		
4	Media: Groundwater:			
	Average Sample Depth	30 FT		
	Sampling Locations	12	9	7
	Samples per Location	1	1	1
	Rounds	4	4	4
	Methodology	Wells – Pumps		
5	Media: Groundwater:			
	Average Sample Depth	30 FT		
	Sampling Locations	135	68	34
	Samples per Location	1	1	1
	Rounds	4	4	4
	Methodology	Power Auger		
6	Laboratory Configuration	Conventional		

Notes:

1. Sampling locations refers to the number of samples to be collected during each testing exercise
 - a. Groundwater = number of wells within each area (100%/50%/25%), including MW-1
 - b. Soil = one sample collected every 25FT x 25FT area
2. Number of Events refers to how many times the monitoring procedure is to be carried out per year
 - a. Groundwater: once quarterly (4 times) in the first year, then once annually for 5 years
 - b. Soil = once in the first year, and once annually for 5 years

B: Capping & Slurry Wall

B-1: Capping Cost Estimation Parameters

S/No	Parameter Description	User Input
1	Type of Cap	RCRA C (Hazardous Waste) Cap
2	Site Area	1.35 Acres
3	Side Slope	3:1 (Default)
4	Horizontal Projection of Side Slope	43FT (Default)
5	Horizontal Projection of Top Slope	43FT (Default)
6	Surface Layer: Type/Thickness/Source	Vegetated Layer/6Inch/Offsite
7	Projection Layer/Source	24Inch/Offsite
8	Drainage Type	Geocomposite
9	Composite Barrier: Geomembrane	40 Mil HDPE
	Compacted Clay Layer	Geosynthetic Clay Layer
10	Foundation Layer: Thickness/Source	12Inch/Offsite

B-2: Slurry Wall Installation Cost Estimation Parameters

S/No	Parameter Description	User Input
1	Wall Length	1612 FT
2	Wall Depth	30 ft
3	Soil Type	Sand-Silt/Sand-Clay Mixture
4	% Weight of Slurry/% Volume of Backfill	9%/6% (Default)
5	Width of Wall	3FT (Default)
6	% Slurry Loss due to Seepage	30% (Default)
7	Working Surface Width	75FT (Default)
8	% of Insufficient Fines Content	35% (Default)
9	% of Contaminated Soil	0% (Default)
10	Foundation Layer: Thickness/Source	12.0Inch/Offsite

B-3: Groundwater Monitoring Wells Cost Estimation Parameters

S/No	Parameter Description	User Input
1	Number of Aquifers	1
2	Depth to Groundwater	30
3	Number of Wells	11
4	Average Well Depth	35 LF
5	Formation Type	Unconsolidated
6	Drilling Method	Air Rotary
7	Well Diameter	2 Inch
8	Well Construction Material	Stainless Steel

Note: See description for A-5 above

B-4: Monitoring Cost Estimation Parameters – Capping & Slurry Wall

S/No	Parameter Description	User Input	
1	Media	Groundwater & Subsurface Soil	
2	Groundwater Monitoring:		
	Average Sample Depth	30 ft	
		1 st year	Out years
	Samples per Event	12	12
	Number of Events	4	1
	Number of Years	1	15
	Number of wells/Day	8 (Default)	
	Sampling Method	Existing Wells – Low Flow Pumps	
3	Subsurface Soil:		
	Average Sample Depth	30 ft	
		1 st year	Out years
	Samples per Event	135	135
	Number of Events	1	1
	Number of Years	1	15
	Number of Samples/Day	7 (Default)	
	Sampling Method	Direct Push Rig	

Note: See description for A-6 above, note however that the out years monitoring duration for this technology alternative is 15years.

B-5: Additional Testing (RCRA Facility Investigation) Cost Estimation Parameters

S/No	Parameter Description	User Input
1	Task description	Sampling and Analysis
2	Site Complexity	Low
3	Crew Size	1 Field Technician and 1 Professional
4	Media: Groundwater:	
	Average Sample Depth	30 FT
	Sampling Locations	12
	Samples per Location	1
	Rounds	4
	Methodology	Wells – Pumps
5	Media: Groundwater:	
	Average Sample Depth	30 FT
	Sampling Locations	135
	Samples per Location	1
	Rounds	4
	Methodology	Power Auger
6	Laboratory Configuration	Conventional

Note: See description for A-7 above

B: Monitored Natural Attenuation (MNA)

C-1: Monitoring Cost Estimation Parameters - MNA

S/No	Parameter Description	User Input	
1	Media	Groundwater & Subsurface Soil	
2	Groundwater Monitoring:		
	Average Sample Depth	30 ft	
		1 st year	Out years
	Samples per Event	12	12
	Number of Events	4	1
	Number of Years	1	25
	Number of wells/Day	8 (Default)	
	Sampling Method	Existing Wells – Low Flow Pumps	
3	Subsurface Soil:		
	Average Sample Depth	30 ft	
		1 st year	Out years
	Samples per Event	135	135
	Number of Events	1	1
	Number of Years	1	25
	Number of Samples/Day	7 (Default)	
	Sampling Method	Direct Push Rig	

Note: See description for A-6 above; note however that the out years monitoring duration for this technology alternative is 25years.

C-2: Additional Testing (RCRA Facility Investigation) Cost Estimation Parameters

S/No	Parameter Description	User Input
1	Task description	Sampling and Analysis
2	Site Complexity	Low
3	Crew Size	2 Field Technicians
4	Media: Groundwater:	
	Average Sample Depth	30 FT
	Sampling Locations	12
	Samples per Location	1
	Rounds	4
	Methodology	Wells – Pumps
5	Media: Groundwater:	
	Average Sample Depth	30 FT
	Sampling Locations	135
	Samples per Location	1
	Rounds	4
	Methodology	Power Auger
6	Laboratory Configuration	Conventional

Note: See description for A-7 above

VITA

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Scope and Method of Study:

A decision making methodology was used to design and propose several remediation plans for a former hazardous and radioactive waste burial site. The site, situated on a 1.6 acre property located west of 44th Street in Stillwater, Oklahoma, belongs to Oklahoma State University. It was used by the University as a hazardous/radioactive waste burial area for over two decades before alternative disposal options were initiated.

Since its closure, twelve groundwater monitoring wells have been installed on the site, from which periodic groundwater samples have been collected and tested for contamination. Four of the detected contaminants were used as contaminants of concern in this analysis. The contaminants were grouped into three waste categories, chemical, radioactive and mixed, for the purpose of the analysis. A spatial technique was used to estimate the distribution of each contaminant and its probability of occurring at given concentrations around the site.

Five remediation technologies were considered for cleaning the site and their expected monetary values were derived based on prevalent 2009 cost data using preset time periods, a fixed interest rate and defined cost components as cost parameters. A decision tree modeling technique was used to compare possible scenarios, based on cost of implementation, to suggest the least expensive path available to achieve remediation goals.

Findings and Conclusions:

The final results from this project are recommended remediation alternatives with their accompanying costs. It was also found that cost elements such as time and waste characterization were critical to the overall remediation cost of the project.

ADVISER'S APPROVAL: Dr William F. McTernan
